Bellcomm

955 L'Enfant Plaza North, S.W.
Washington, D. C. 20024

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date: June 28, 1971

to: Distribution

from: J. J. Sakolosky

subject: Evaluation of the Skylab Electrical Power System for a Particular Mission Day - Case 620

ABSTRACT

Using models of the paralleled AM and ATM electrical systems, the AM/OWS and ATM solar arrays, the AM power conditioning groups, and the ATM charger-battery-regulator-modules, the performance of the Skylab electrical power system has been studied for a particular mission day. Network properties (currents, voltages, and loads on each spacecraft bus; interface voltages; voltages on each AM regulated bus) and battery charge characteristics have been determined. The mission day studied is an extremely active one, imposing greater power demands than the system would normally see.

A maximum electrical load of 8470 watts occurs during a local vertical pass for earth resources experiments. Several additional peaks in excess of 8000 watts are experienced. The highest orbit average is approximately 7400 watts and the average load over the 24 hour period is 6650 watts.

No-load voltage settings of the AM regulated buses were varied between 28.8 volts and 29.2 volts; the ATM bus voltage setting was held constant at 30.4 volts. An AM setting of 29.0 volts is optimum for equalizing the depth-of-discharge experienced by the AM and ATM batteries. However, the MDA/ATM and MDA/CSM interface voltage constraints are violated for voltage settings of 29.0 volts and less. Increasing the open circuit setting to 29.2 volts raises the interface voltage just enough to meet the requirements.

The maximum depth-of-discharge experienced by the batteries at a voltage setting of 29.2 volts is 31.2% for AM battery bank 1. The average depth-of-discharge for this same bank of batteries is 27.5%. These values decrease to 29.4% and 26.0% respectively when the AM open circuit voltage setting is decreased to 29.0 volts.

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MEMORANDUM FOR FILE

INTRODUCTION

The performance of the Skylab electrical power systems has been studied in detail for an active mission day. The particular 24-hour period chosen consists of seventeen solar inertial orbits and one earth resources orbit with a 120° local vertical pass.

The analysis may be conveniently separated into (1) an investigation of the network properties of the parallel AM and ATM electrical power system, and (2) an examination of the state-of-charge history of each battery bank. The network analysis examines individual spacecraft bus voltages and currents and module interface voltages resulting from power requirements of each spacecraft module. In the state-of-charge analysis, the trajectory, temperature effects, losses due to non-normal solar incidence, shadowing of the AM solar array by the ATM array, and cell degradation have been considered in determining power generated by the AM and ATM solar arrays as a function of time. Using the solar array power profile and the electrical load profile (from the network analysis) for each power system, a state-of-charge profile for the AM and ATM batteries was determined. The general approach used is illustrated in Figure 1.

Description of Chosen Mission Day

The crew activities timeline used for this study is shown in Figure 2, which is taken from Reference 1. This timeline is in turn based on sample trajectory data from Reference 3 that covers the 24-hour period beginning 9 days 9 hours GET after the assumed launch of Skylab 1 on July 19 at 1500 hours. A wide range of activities and experiments have been included, representing a substantial portion of the operations that will occur during a mission, and probably more than will actually ever be scheduled during a single mission day. Reference 1 contains a complete description of the day under consideration.

Trajectory data (sun angle, times of sunset, sunrise, noon) were obtained from Reference 3. The minimum angle between the sun vector and the orbital plane, β, varies from $-17.92°$ to $-21.14°$ during the 24 hours of interest.* β is $-19.5°$ during the earth resources orbit.

A solar inertial (SI) attitude is maintained during the sunlit portion of all orbits except the one orbit during which earth resources experiments are performed. The maneuver into a local vertical attitude for earth resources experimentation begins at sunrise of the ninth revolution and is completed at a point in the orbit 60° before orbital noon. Local vertical attitude is maintained until 60° past the noon position when the maneuver back to solar inertial is initiated. The return maneuver is completed by the time the sunset terminator is reached.

The timeline of Figure 2 results in three periods of unusually high power requirements: (1) during the performance of medical experiments M071, M073, M074, and M172 following breakfast ($\sim$234. hrs GET); (2) during the performance of the earth resources experiments ($\sim$238. hrs GET); and (3) during the ATM experiment operations ($\sim$241.-242. hrs GET). Because of the variety of activities scheduled, and because of some conservative assumptions used to generate them, large swings exist in the power requirements profile.

Network Analysis

The power which must be delivered by each of the AM regulated buses and by the ATM buses is computed by a network analysis program. Loop equations are utilized to solve for loop currents and node voltages in a network model (Figure 3) of the paralleled AM/OWS and ATM electrical power systems. Equivalent constant resistance loads (e.g., RAML1, RAML2, RMDA1, ROWS1, etc.) on each spacecraft bus are computed from a bus power requirements profile using an assumed bus voltage of 28 volts. The open circuit supply bus voltages VAM1, VAM2, VATM and the network line resistance values are program inputs; the supply voltages may be varied to optimize the load sharing characteristics of the two parallel systems.

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*The sun angle, β, is negative when the sub-solar point is south of the sub-orbital noon point as illustrated in Figure 4.

The power requirements profiles used to compute the equivalent constant resistance load on each spacecraft bus are based on the crew activities timeline of Reference 1. The 24 hour sample day was divided into six-minute increments during which power requirements were assumed to remain constant. Power peaks and transients of shorter duration were averaged over the six minute period. The requirements of each operating subsystem were determined from the appropriate power allocation document for that spacecraft module (References 8, 9, 10, and 11). A number of assumptions were made concerning subsystem, component, and experiment operating times and duty cycles; they are summarized in Reference 7. Figure 6 of Reference 12 was used in assigning each load to the proper module bus.

The resultant power which must be delivered by each AM regulated bus and the ATM buses is shown in Figures 8, 9, and 10 for open circuit voltage settings of VAM1 = VAM2 = 28.8 volts and VATM = 30.4 volts. The average load on AM regulated bus 1 is approximately 1500 watts, the load on AM bus 2 approximately 1350 watts, and the average ATM load about 3700 watts. The maximum power required from either AM regulated bus is 2400 watts, which occurs at bus 1 during earth resources experiments. The ATM buses must supply a maximum power of 4200 watts during ATM experiment operations. When the AM no-load voltage settings are increased to 29.2 volts, the load on each of the AM regulated buses increases by 200-300 watts, and the ATM load decreases by approximately 500 watts average (see Figure 11).

Total power, including system losses, delivered by both AM regulated buses and by the ATM buses is shown in Figure 13. The peaks invariably occur during the dark portion of each orbit. This results from the conservative assumption that high electrical heating requirements occur during each night cycle. A maximum load of 8470 watts occurs during the earth resources experimentation period. Additional peaks in excess of 8000 watts occur during the medical experimentation period and during performance of the solar astronomy experiments. The average load over the 24 hour period is approximately 6650 watts.

In Appendix A, the actual loads on all spacecraft buses and on the orbital vehicle power transfer buses are detailed. Bus voltages and currents and the MDA/CSM and MDA/ATM interface voltages are also examined.

Solar Array Power Generation-Earth Resources Orbit

The following equation, from Reference 4, was used to calculate the power produced by each solar array.

$$P_{SA} = P_N(T) \cdot \cos\lambda \cdot (1-L_S) \cdot (1-L_R) \cdot (1-L_D) \qquad (1)$$

$P_N(T)$ - temperature dependent solar array power at normal (i.e., perpendicular) solar incidence, air mass zero, and beginning of life.

$$\text{OWS:} \quad P_N(T) = 15350\ (1-.00258(T-82.4°F))\ \text{watts} \qquad (2)$$

$$\text{ATM:} \quad P_N(T) = 11855\ (1-.00258(T-86.0°F))\ \text{watts} \qquad (3)$$

The local vertical (LV) temperature profile and curve-fit equations of Reference 4 were used in the above equations for orbit position angles between η=-15° and η=+60°. The orbit position angle, η, is measured from orbital noon, positive in the direction of orbital velocity. The angle η is illustrated in Figure 4. A linear transition applicable only to the present case of β=-19.5° was used to convert from the SI temperature profile at sunrise to the LV profile at η=-15°. For η greater than +60°, a non-linear transition (also applicable only to the value of β for this particular earth resources orbit) was used to convert back to a SI temperature profile.

For the purposes of this analysis, the temperature profile of the ATM solar array was assumed to be the same as that of the OWS array. The assumption is based on data presented at the Critical Design Review of the ATM thermal control system on May 13, 1970. The data indicate a range of temperature values for any particular orbital position, the mid-range value closely approximating the temperature of the OWS array under corresponding conditions.

$\cos \lambda$ - accounts for reduction in solar array power output due to non-normal solar incidence. The angle λ is between an outward normal to the solar array and a vector to the sun.

$$\cos \lambda = \cos \phi \cos (\eta - \theta) \cos \beta + \sin \phi \sin \beta \tag{4}$$

An equation similar to (4) is derived in Reference 6 which used a different coordinate system. The angles β and η have been previously defined. The angles θ and ϕ are defined relative to a reference local vertical coordinate system shown in Figure 4. θ, formed by a negative rotation about the normal to the orbit plane, Y_{LV}, is the angle between the spacecraft X-axis and X_{LV}, which is tangent to the orbital plane. A negative rotation about the spacecraft X-axis then produces the roll angle ϕ. It is the angle formed between the spacecraft Y-axis and Y_{LV}, or in other words, the angle formed between the plane of the spacecraft solar arrays and the normal to the orbital plane. The spacecraft coordinate system is defined in Figure 5.

$(1-L_S)$ - accounts for reduction of AM/OWS solar array power generation capability as a result of shadowing by the ATM array. No shading of the ATM array is assumed. The shadowing program of Reference 6 has been used in conjunction with the attitude profile given by Reference 2 to determine the percentage of the total area of the AM/OWS array shaded at each orbital position. Because the solar cells of the AM/OWS array are connected in series strings of 154 cells, shading of one or more cells per string eliminates the power generation capability of the entire string. Therefore, the percentage area shaded must be adjusted by a corrective factor to obtain a realistic estimate of the actual decrease in power generation capability. Based on data obtained for the number of strings affected by various given shadow patterns, the corrective factor actually varies over a range of values between 1.3 and 2.0. However, it is most often nearly 1.5, and that is the value which was used in this work.

$(1-L_R)$ - accounts for solar array power reduction due to reflective loss (L_R) from the quartz cover slides at non-normal solar incidence. The variation of $(1-L_R)$, the normalized transmittance, as a function of λ has been determined in Reference 4.

$(1-L_D)$ - accounts for reduction in cell solar-to-electrical conversion efficiency as a function of exposure time to environmental radiation. For the chosen day of interest in this analysis, $(1-L_D)$ is constant at .9983, which is based on 0.5% per month degradation.

Solar Array Power Generation - Solar Inertial Attitude

Equation (1) simplifies considerably for the case when the spacecraft is in a solar inertial attitude. The shaded portion of the AM/OWS array is constant and λ equals zero. The last four terms of (1) are then

$$\cos \lambda = 1.0$$

$$(1-L_S) = .9745$$

$$(1-L_R) = 1.0$$

$$(1-L_D) = .9983$$

$P_N(T)$, the only non-constant term, is given by equations (2) for the AM/OWS array and (3) for the ATM solar array. Array temperature data for the sunlit portion of the orbit was obtained from Reference 5, and curves were fit to the data to simplify operation within the computer program. Appendix B gives the equations for the resultant curves.

Determination of Battery State-of-Charge

The charge flowing to or from each battery may be represented simply as

$$\Delta C = \frac{\Delta E}{V_B} = \frac{P\Delta t}{V_B} \tag{5}$$

where ΔC = incremental charge, ampere-hours

ΔE = incremental energy, watt-hours

P = power level of energy to/from battery, watts

V_B = battery voltage, volts

Δt = incremental time, hours

The power conditioning groups (PCG's) of the AM electrical power system and the charger-battery-regulator modules (CBRM's) of the ATM system have been modeled as shown in Figure 6 and Figure 7. Each model in conjunction with the basic equation (5) gives rise to the following state-of-charge equations for the corresponding power system. Note that the following equations, unlike equation (5), calculate the incremental charge in terms of a percentage of total system capacity.

AM/OWS SYSTEM

Charge: $$\Delta C = \frac{100 \cdot \Delta t}{E_B \cdot AH \cdot N} \left(\eta_{R1} P_{SA} - \frac{P_L}{\eta_D \eta_{R4} \eta_R \eta_{R3} \eta_C} \right) \eta_C \eta_{R2} \eta_B \tag{6}$$

Discharge: $$\Delta C = \frac{100 \cdot \Delta t}{E_B \cdot AH \cdot N} \left(\frac{P_L}{\eta_D \eta_{R4} \eta_R \eta_{R3}} - \eta_{R1} \eta_C P_{SA} \right) \frac{1}{\eta_{R2}} \tag{7}$$

ΔC - incremental change in battery state-of-charge, %

E_B - nominal battery voltage = 34.5 volts

AH - rated ampere-hour capacity/battery = 33 amp-hrs

N - number of batteries/regulated bus = 4

Δt - time increment, hours

P_L - electrical load/regulated bus, watts

P_{SA} - power generated by one-half of the AM/OWS solar array, watts

The definition and value of each of the efficiencies, η, is given in Figure 6.

The electrical power system in the AM provides for the connection of eight PCG's to either of two regulated buses. In the usual mode of operation four PCG's are tied to each bus. Regulated voltage at the buses may be adjusted by the crew to vary the proportion of the total load shared by each of the AM/OWS and ATM power systems.

Each regulated bus and bank of four AM batteries is treated separately in this analysis. P_L in equations (6) and (7) (the actual load including distribution losses) is computed for each AM bus by the network analysis program. Accordingly, P_{SA} is exactly one-half of the power generation capability of the AM/OWS solar array.

ATM SYSTEM

Charge: $$\Delta C = \frac{100 \cdot \Delta t}{E_B \cdot AH \cdot N} \left(\eta_{R1} P_{SA} - \frac{P_L}{\eta_D \eta_{R3} \eta_R} \right) \eta_C \eta_{R2} \eta_B \qquad (8)$$

Discharge: $$\Delta C = \frac{100 \cdot \Delta t}{E_B \cdot AH \cdot N} \left(\frac{P_L}{\eta_D \eta_{R3} \eta_R} - \eta_{R1} P_{SA} \right) \frac{1}{\eta_{DI} \eta_{R2}} \qquad (9)$$

ΔC - incremental change in battery state-of-charge, %

E_B - nominal battery voltage = 27.6 volts

AH - rated ampere-hour capacity/battery = 20 amp-hrs

N - number of batteries = 18

Δt - time increment, hours

P_L - electrical load, watts

P_{SA} - power generated by the ATM solar array, watts

The definition and value of each of the efficiencies, η, is given in Figure 7.

The ATM electrical power system is configured so that each of eighteen CBRM's is connected through diodes to two collector buses. Each collector bus feeds a load bus and subsequent distribution circuitry to the load, thus forming a parallel distribution system from each CBRM to the load. The load on each ATM bus is assumed to be shared equally among the eighteen CBRM's.

The battery charger limits the current to the ATM batteries to 15 or less amperes during the charge cycle. Therefore, there will be times (e.g., following sunrise) when the batteries cannot accept all of the power available for recharging. This analysis limits the recharge power to the batteries to 8500 watts - 18 batteries x 15 amps x 31.5 volts (maximum battery voltage during constant current recharge).

Battery State-of-Charge Profiles

Time profiles for the power produced by one-half of the AM/OWS solar array, the electrical load on AM regulated bus 1, and the state-of-charge for the four corresponding batteries are shown in Figure 8. Figure 9 shows similar data for AM regulated bus 2 and its batteries. The data are for an open circuit voltage setting of 28.8 volts on each AM regulated bus and 30.4 volts on the ATM buses. Figure 10 illustrates the corresponding ATM data for this same case.

The maximum depth-of-discharge (DOD) experienced by the AM batteries is 27.5% and occurs at 234.3 hrs GET during the performance of medical experiments M071, M073, M074, and M172. A DOD of 26% in each AM battery bank is reached during ATM experiment operations (∿242 hrs GET). During this same period the ATM batteries reach a DOD of 29.5%, the maximum they experience during the chosen day.

During the earth resources pass, 237.3 hrs to 238.3 hrs GET, power generated by each solar array drops off rapidly as the maneuver into local vertical is initiated. Having acquired the earth resources attitude, an intermediate peak occurs at noon followed by another drop in power until the return to solar inertial begins. This decrease in available power in conjunction with the additional experiment load acts to substantially reduce the rate at which the batteries are recharged. Nevertheless, complete recovery of both the AM and the ATM batteries is achieved by sunset.

The average depth-of-discharge of each bank of batteries for the 24 hour period is 24.5% for AM1, 23.0% for AM2, and 26.5% for the ATM. Except for the earth resources orbit, the AM batteries are invariably fully charged before noon of each orbit; the ATM batteries reach full charge shortly after noon.

Figure 11 illustrates the load on each AM regulated bus and the ATM load when the open circuit voltage setting of the regulated buses is increased to 29.2 volts. The corresponding state-of-charge profiles are shown in Figure 12. The maximum DOD of the AM batteries increases to 31.2% (battery bank 1) during performance of the medical experiments. The same bank of batteries reaches a DOD of 30.4% during the ATM experiment operations. The ATM batteries reach a maximum DOD of 26.7% during ATM operations. The average depth-of-discharge for each bank of batteries at the end of the 24 hour period is 27.5% for AM1, 26.0% for AM2, and 24.1% for the ATM. Except for the earth resources orbit, each bank of batteries is fully recharged before noon of each orbit. Table 1 summarizes maximum and average depth-of-discharge data for various open circuit voltage settings.

TABLE 1

DEPTH-OF-DISCHARGE IN PERCENT OF AM AND ATM BATTERIES FOR VARIOUS AM REGULATED BUS VOLTAGE SETTINGS AND VATM=30.4 VOLTS

	Maximum DOD			Average DOD		
VAM1 = VAM2	AM1	AM2	ATM	AM1	AM2	ATM
28.8 volts	27.5	26.2	29.5	24.5	23.0	26.5
29.0 volts	29.4	28.0	28.1	26.0	24.4	25.3
29.2 volts	31.2	29.9	26.7	27.5	26.0	24.1

Summary and Conclusions

The 24 hour period chosen for this analysis represents a heavily loaded day in a Skylab mission. The total average electrical load is in excess of 6500 watts with a worst orbit average load of approximately 7300 watts (for VAM1 = VAM2 = 28.8 volts). The peak load averaged over a 6 minute period is 8470 watts. The assumption that electrical heaters are cycled on during the dark portion of each orbit results in relatively high depths-of-discharge. Nevertheless, the batteries associated with each power system are fully recharged each orbit, usually before noon or shortly thereafter. During the earth resources orbit the time of full recharge occurs significantly later but still before sunset.

The rate of recharge during the sunlit portion is lower for the ATM batteries than for the AM. One reason for this is the 15 ampere current limit imposed on the ATM batteries during the recharge cycle. Better definition of battery charge rate as a function of time, battery temperature, and available array power is needed for both electrical power systems and would provide the basis for an improved battery-charger model over the simple one used here. This is an appropriate area for future work.

Varying the open circuit voltage setting of the AM regulated buses provides an effective way of equalizing the average depth-of-discharge between the AM and ATM battery banks. The difference between AM and ATM battery average DOD is about 3.5% at open circuit voltage settings of both 28.8 volts (AM DOD < ATM DOD) and 29.2 volts (ATM DOD < AM DOD). A voltage setting of 29.0 volts is near optimum for balancing both systems. Unfortunately, the MDA/CSM and MDA/ATM interface voltage requirements are violated for open circuit voltage settings of 29.0 volts and below (see the voltage profiles of Figure A4). When the open-circuit settings are increased to 29.2 volts, no violations occur, but the voltage margins are negligible and maximum DOD for AM battery bank 1 exceeds 30%.

Based on a fully operational system, this study indicates that adequate electrical power is available from the parallel AM and ATM EPS's to fully meet load requirements while maintaining an energy balance in the AM and ATM batteries. The batteries for each EPS may be maintained at approximately the same depth-of-discharge if such operation is deemed desirable. However, to do so may require a violation of the MDA/CSM and MDA/ATM interface voltage requirements. Additional investigation in this area is recommended.

Acknowledgement

B. W. Moss developed the network model for the parallel configuration of the AM and ATM electrical power systems and made a major contribution toward computation of the power requirements profile for each module bus before leaving the company. W. W. Hough provided substantial assistance in completing the power requirements profiles and helpful discussion and suggestions concerning the rest of the work. Mrs. P. R. Dowling wrote the computer programs for both the network analysis and the state-of-charge analysis.

James J. Sakolosky

1022-JJS-jf

J. J. Sakolosky

Attachments
References
Appendices A and B

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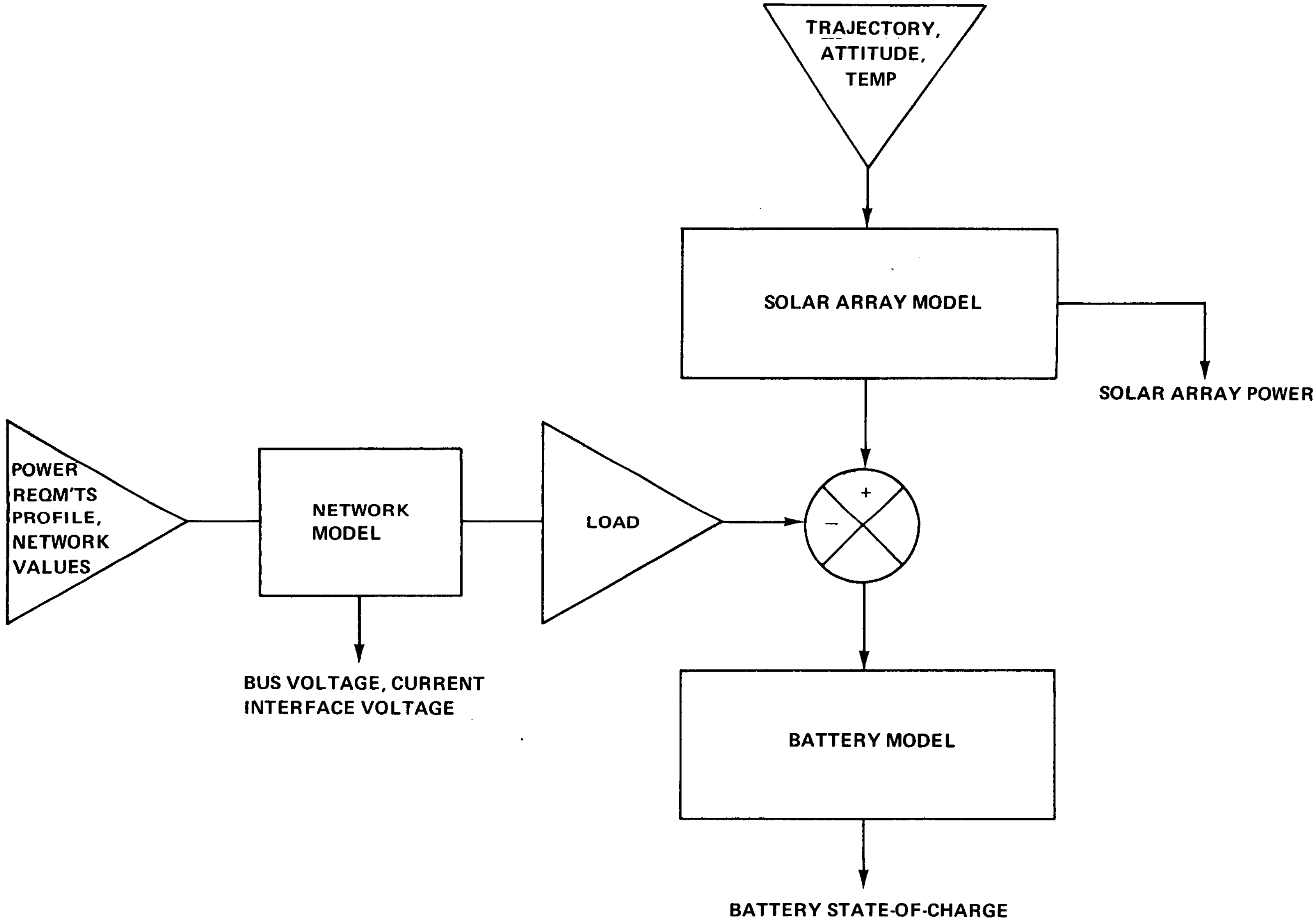
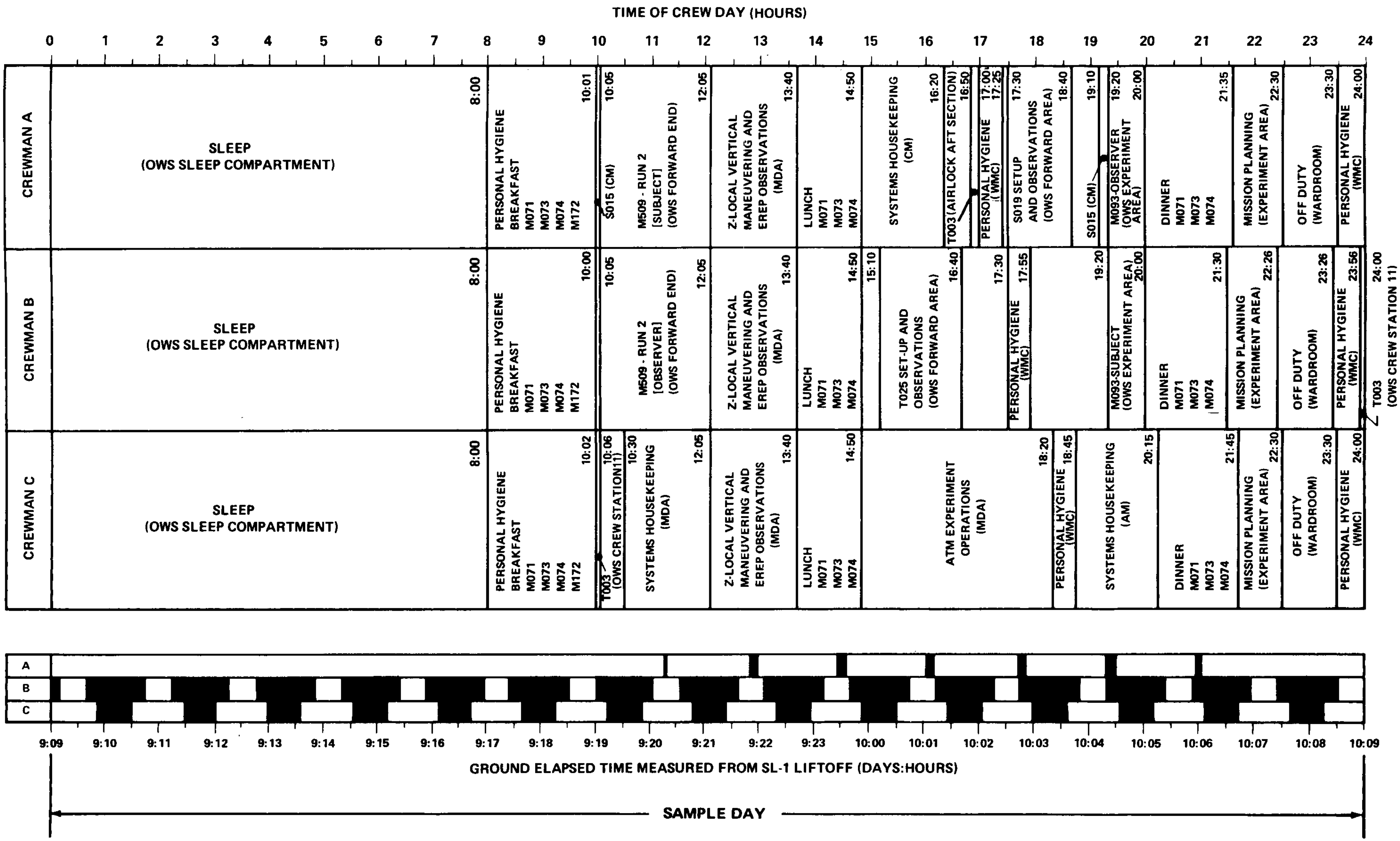


FIGURE 1 - SIMPLIFIED MODEL ILLUSTRATING APPROACH USED IN ANALYSIS OF SKYLAB ELECTRICAL POWER SYSTEMS



A ≡ SPACECRAFT PASSES OVER CONTINENTAL U.S.A. (BLACK REGION OF TIMELINE)

B ≡ SOLAR ELEVATION AT SPACECRAFT SUBPOINT ≥ 30° (WHITE REGION OF TIMELINE)

C ≡ SUN DIRECTLY VISIBLE FROM SPACECRAFT (WHITE REGION OF TIMELINE)

FIGURE 2 - INTEGRATED SKYLAB FLIGHT—CREW TIMELINES FOR THE PICK A DAY STUDY

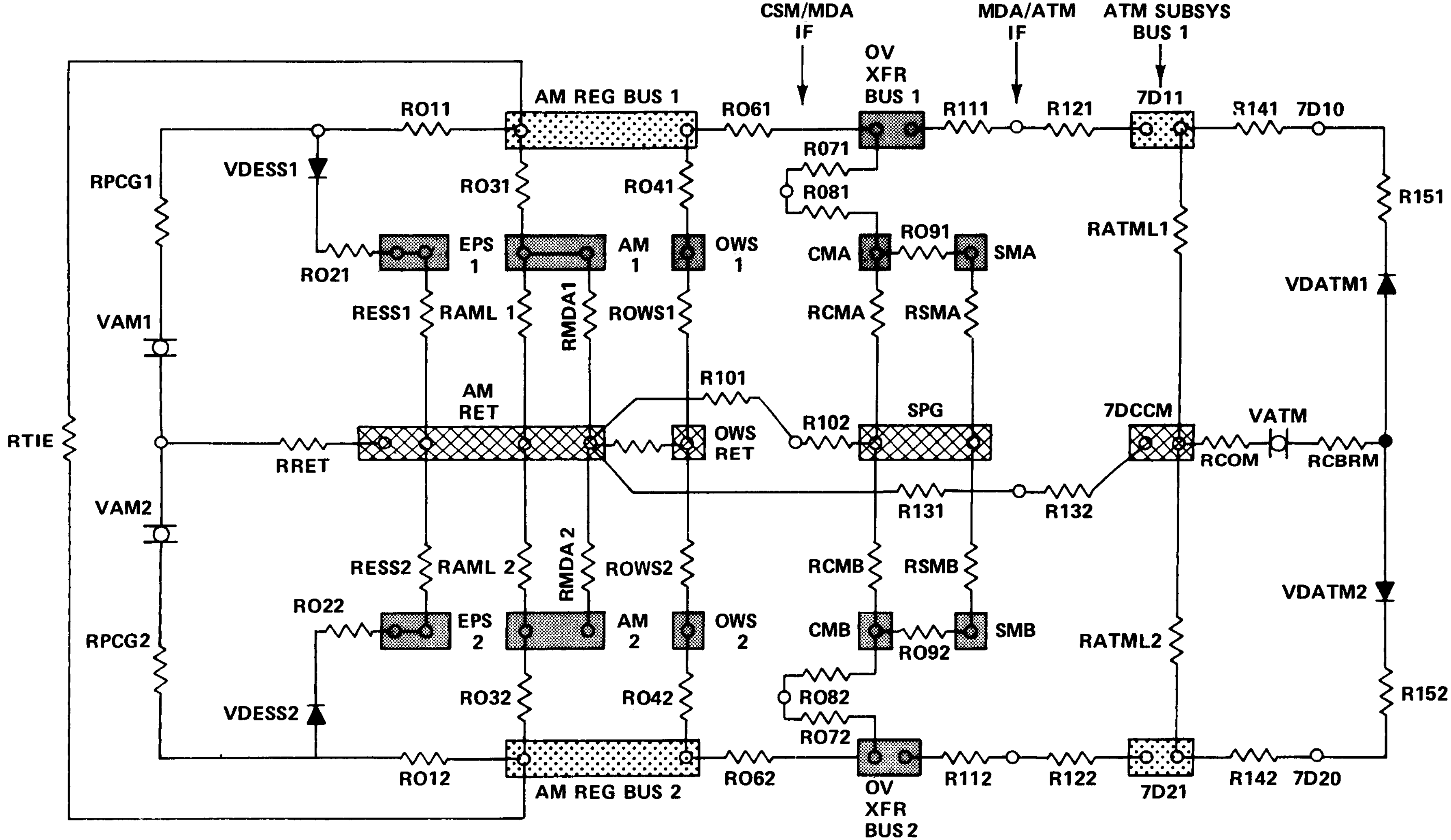


FIGURE 3 - NETWORK MODEL OF SKYLAB POWER DISTRIBUTION SYSTEM

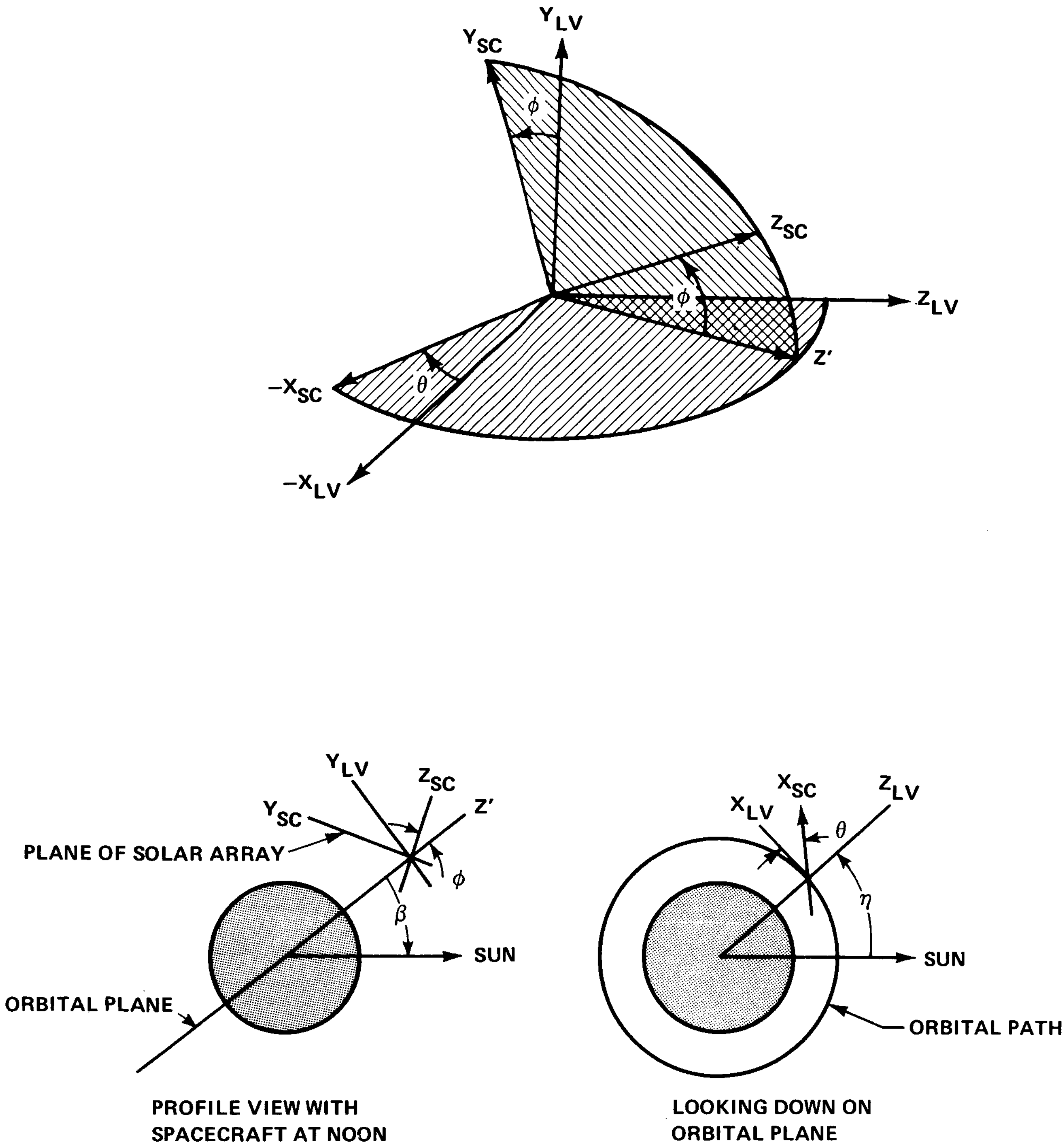


FIGURE 4 - DEFINITION OF ANGLES β, η, ϕ, AND θ

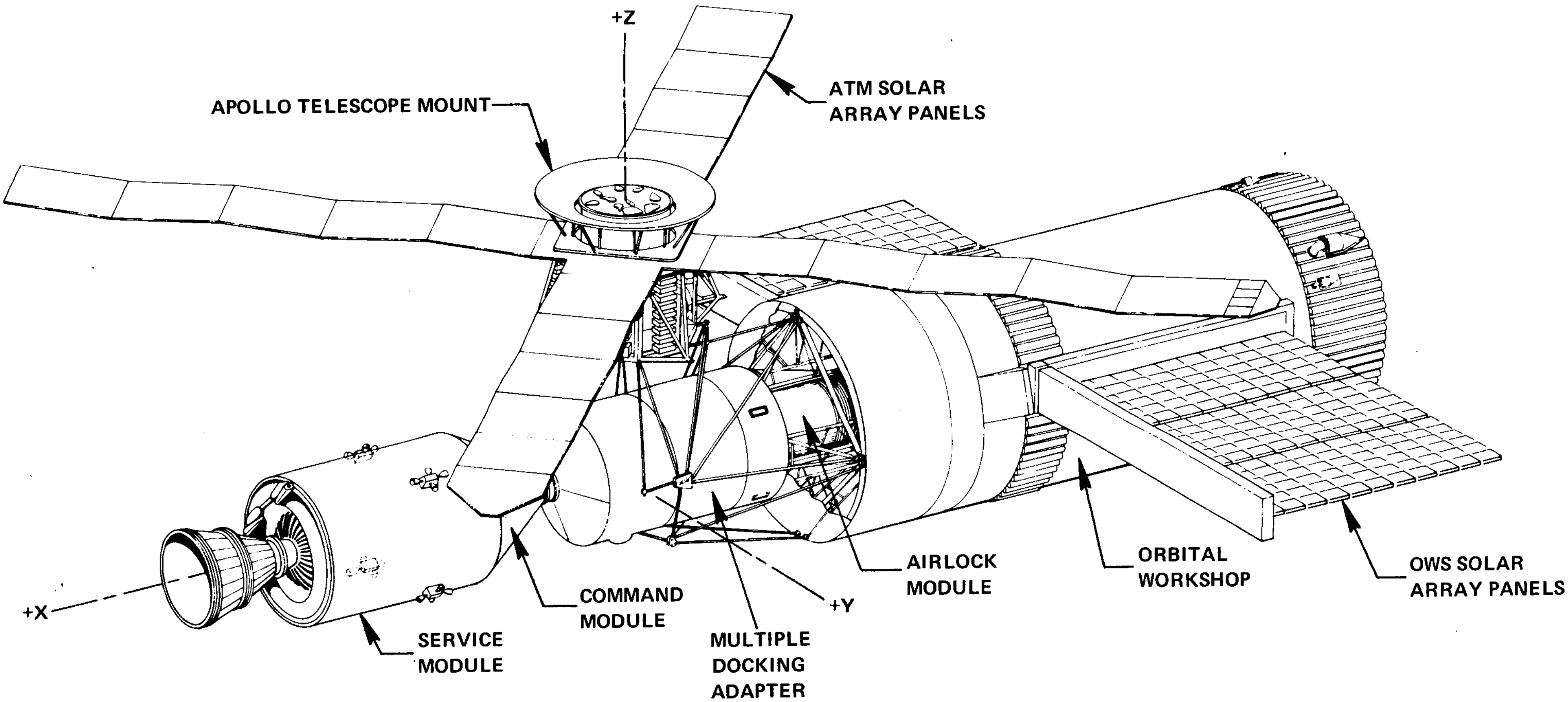


FIGURE 5 - DEFINITION OF SPACECRAFT ATTITUDE CONTROL COORDINATE SYSTEM

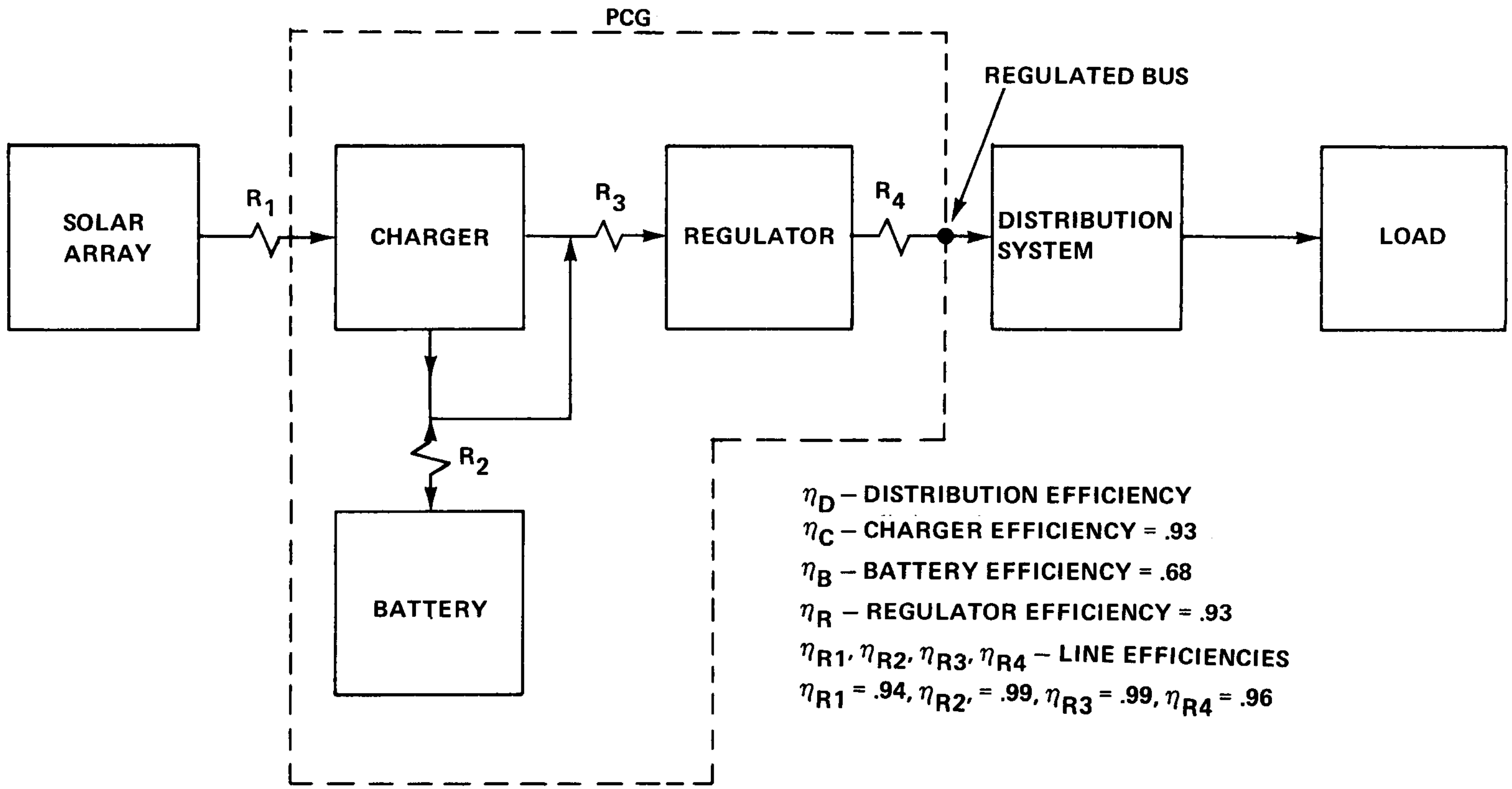
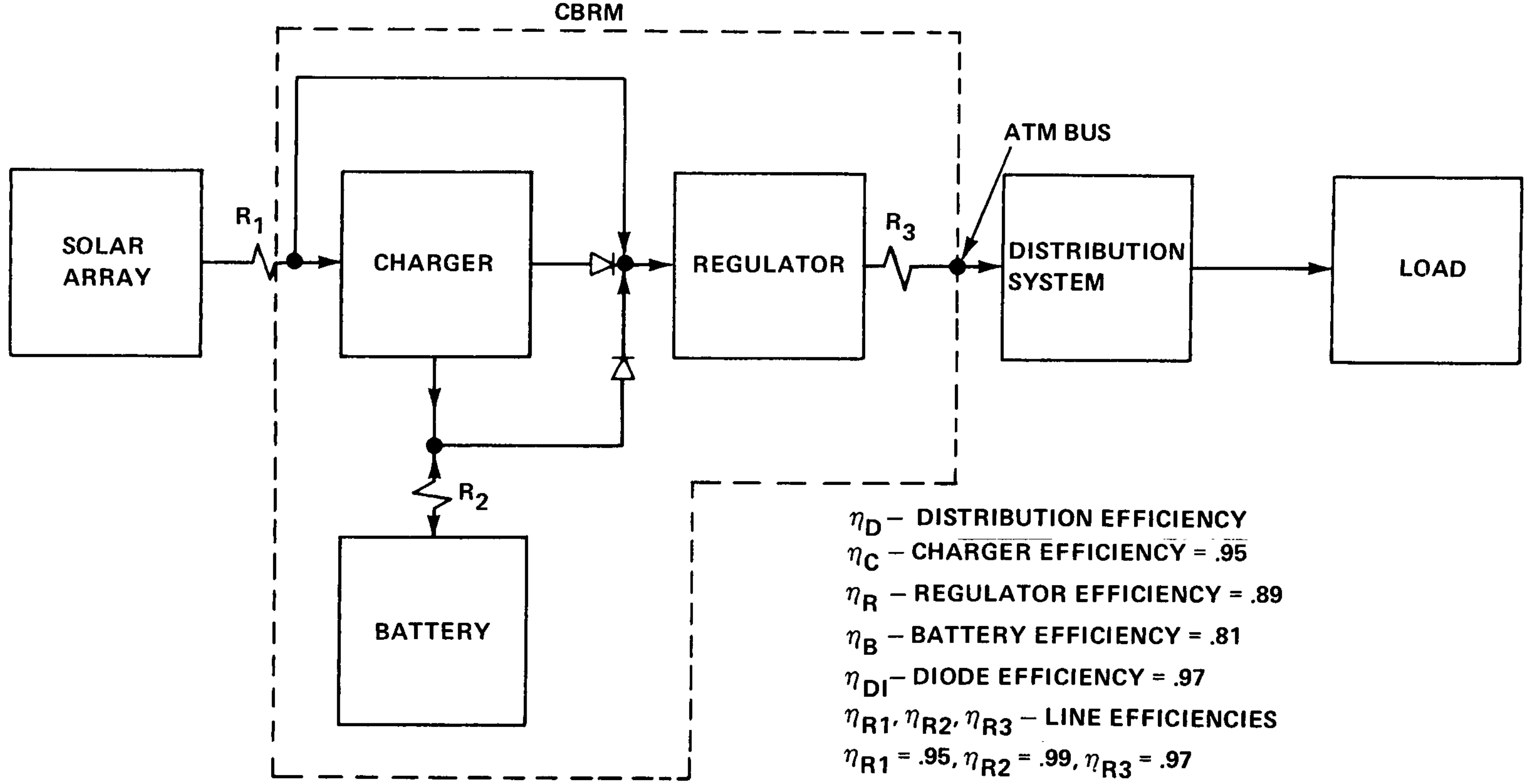


FIGURE 6 - MODEL OF AM/OWS SOLAR ARRAY/BATTERY ELECTRICAL POWER SYSTEM



η_D – DISTRIBUTION EFFICIENCY

η_C – CHARGER EFFICIENCY = .95

η_R – REGULATOR EFFICIENCY = .89

η_B – BATTERY EFFICIENCY = .81

η_{DI} – DIODE EFFICIENCY = .97

$\eta_{R1}, \eta_{R2}, \eta_{R3}$ – LINE EFFICIENCIES

$\eta_{R1} = .95, \eta_{R2} = .99, \eta_{R3} = .97$

FIGURE 7 - MODEL OF ATM SOLAR ARRAY/BATTERY ELECTRICAL POWER SYSTEM

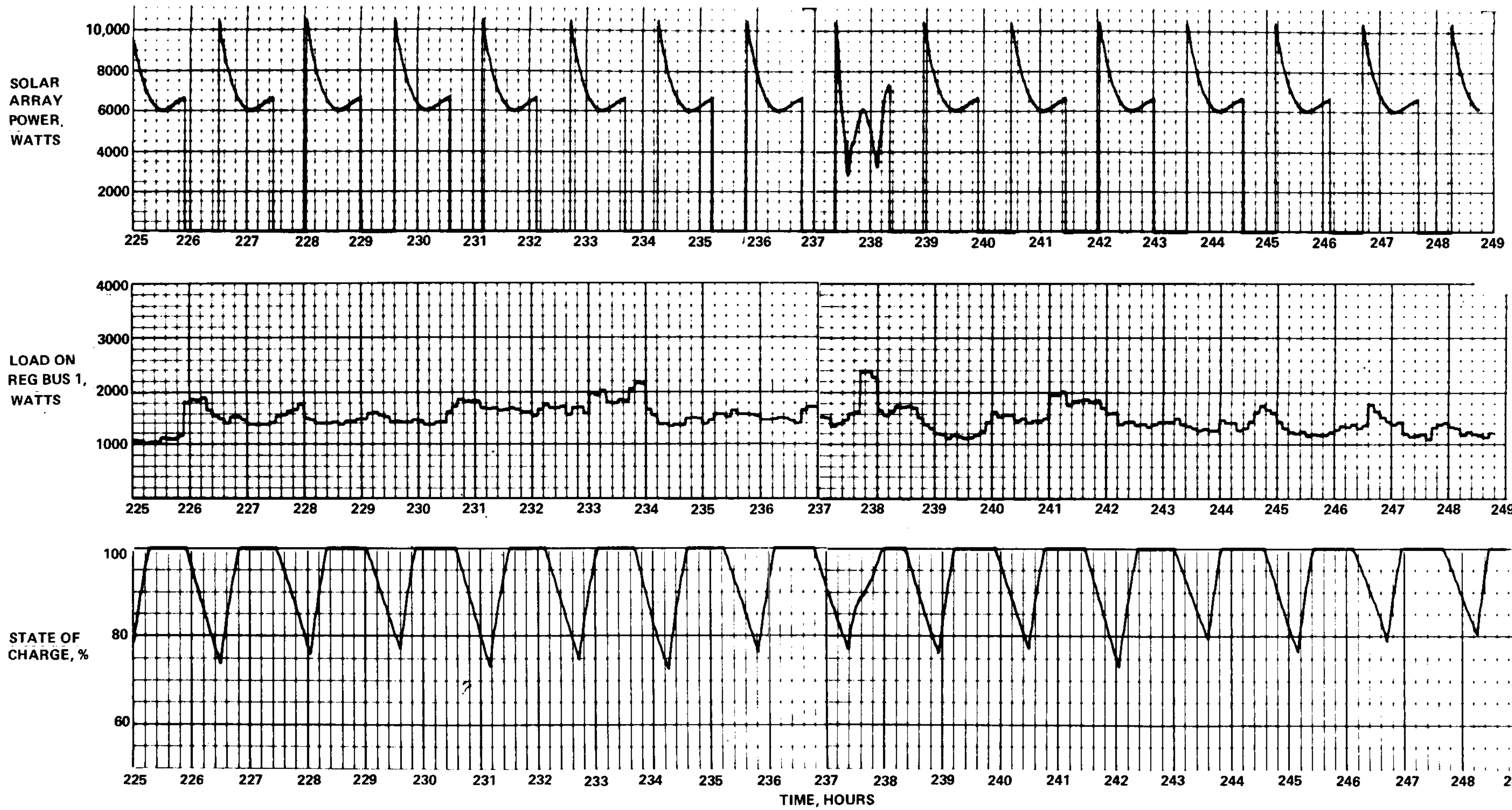


FIGURE 8 - AM/OWS SOLAR ARRAY POWER (ONE-HALF OF TOTAL), LOAD ON AM REGULATED BUS 1, AND STATE-OF-CHARGE OF AM BATTERY BANK 1 FOR VAM1 = VAM2 = 28.8 VOLTS AND VATM = 30.4 VOLTS

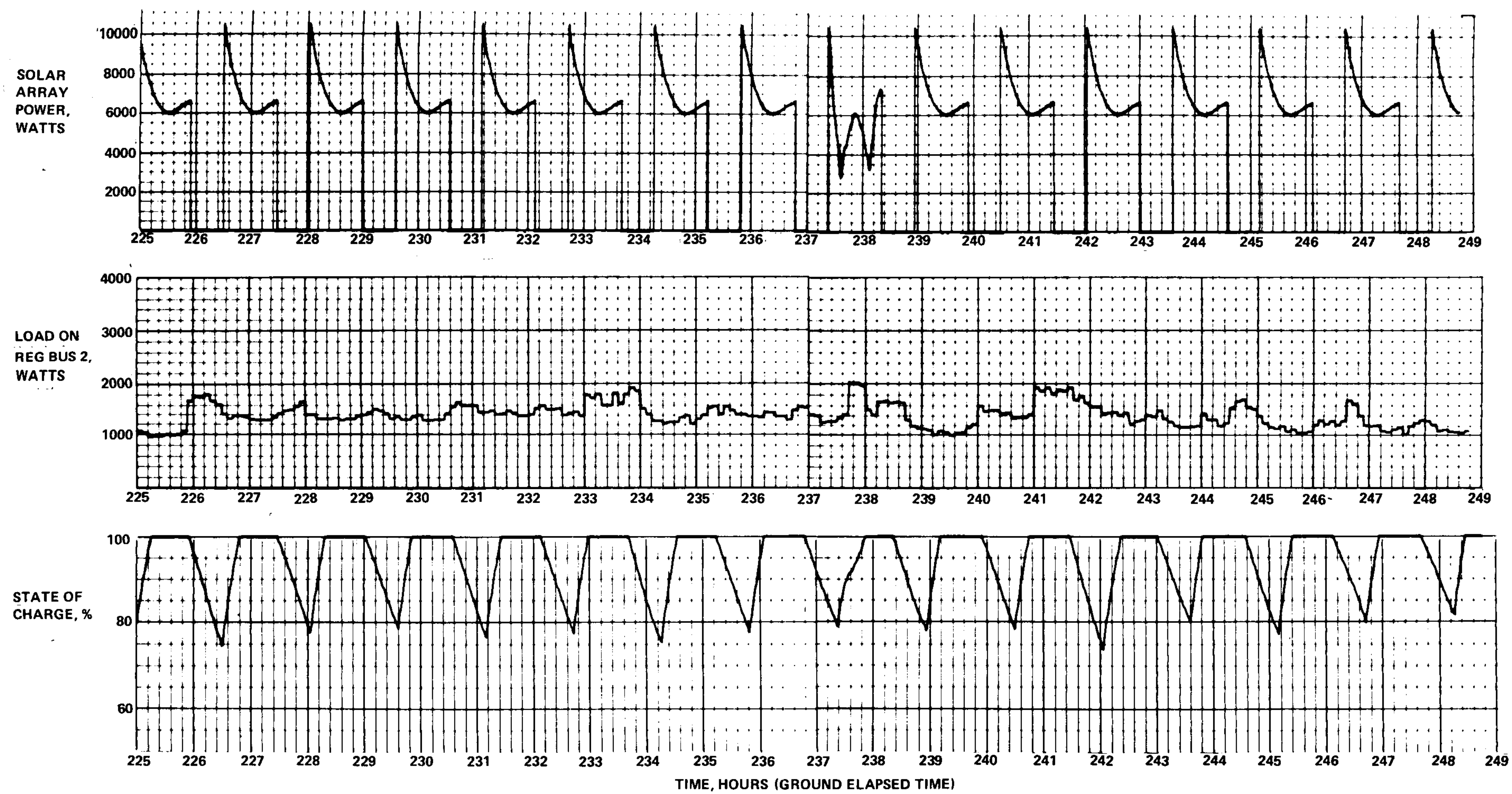


FIGURE 9 - AM/OWS SOLAR ARRAY POWER (ONE-HALF OF TOTAL), LOAD ON AM REGULATED BUS 2, AND STATE-OF-CHARGE OF AM BATTERY BANK 2 FOR VAM1 = VAM2 = 28.8 VOLTS AND VATM = 30.4 VOLTS

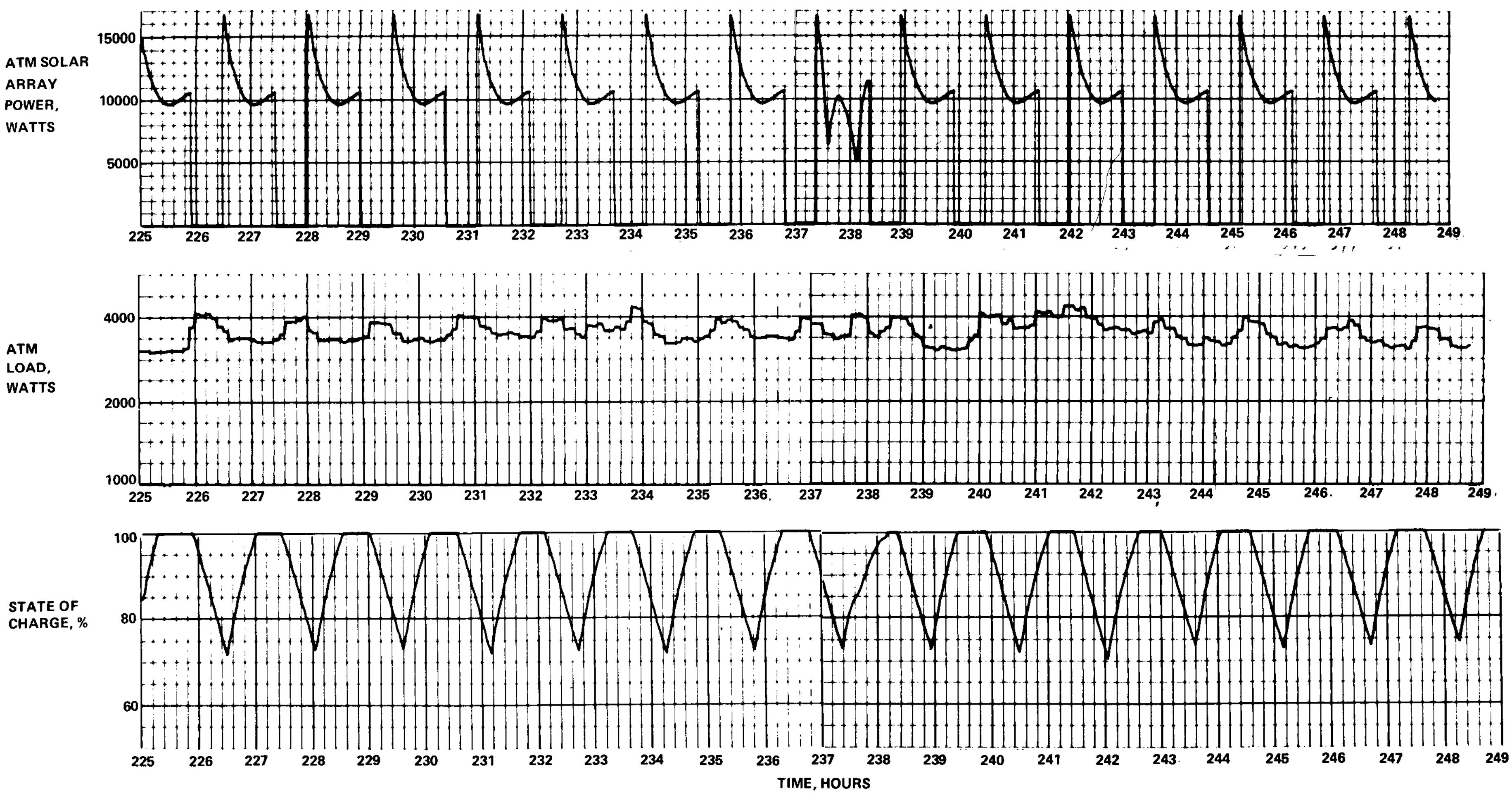


FIGURE 10 - ATM SOLAR ARRAY POWER, ATM LOAD, AND STATE-OF-CHARGE OF ATM BATTERIES FOR VAM1 = VAM2 = 28.8 VOLTS AND VATM = 30.4 VOLTS

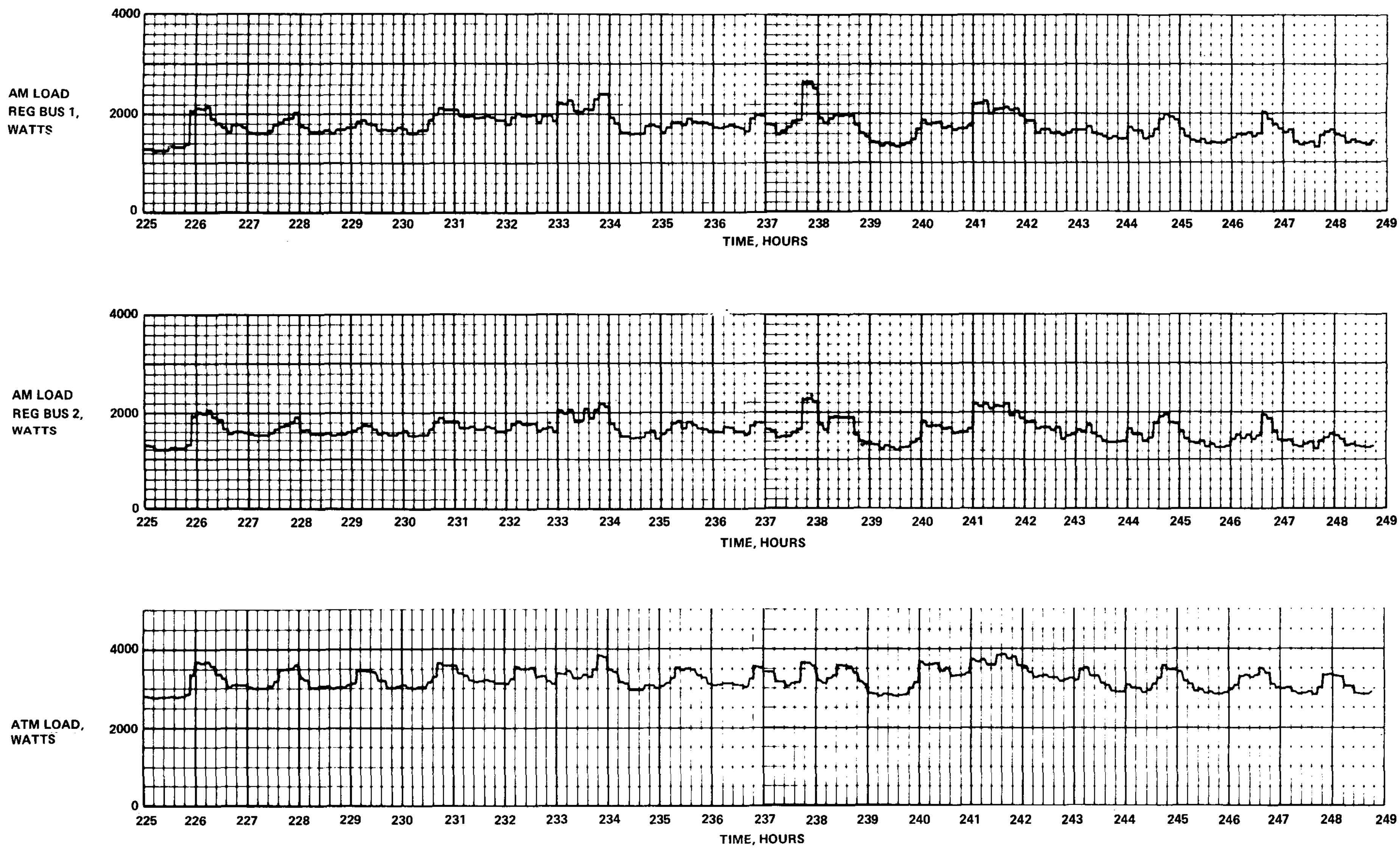


FIGURE 11 - LOAD ON AM REG BUS 1, AM REG BUS 2, AND ATM LOAD FOR VAM1 = VAM2 = 29.2 VOLTS AND VATM = 30.4 VOLTS

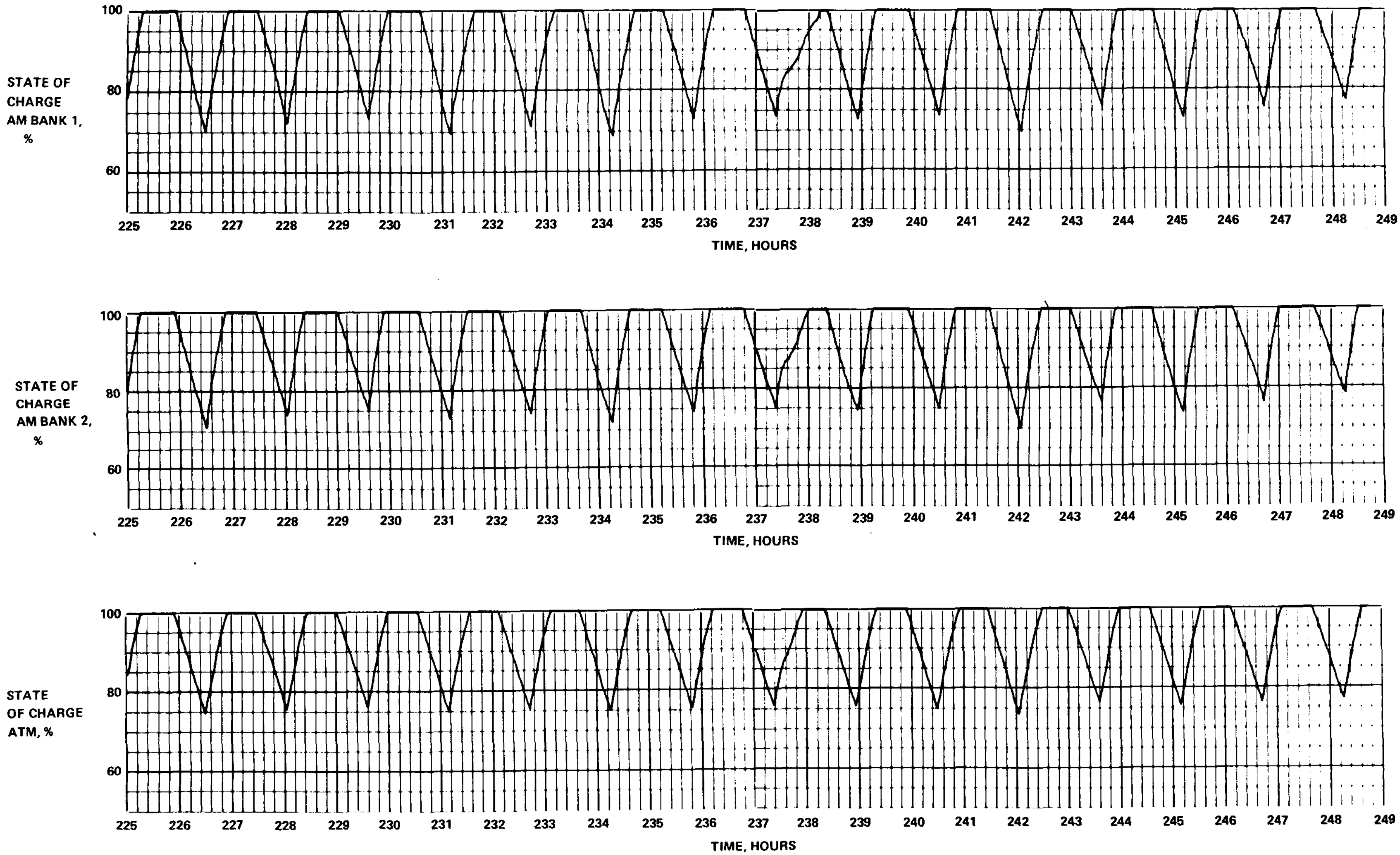


FIGURE 12 - STATE-OF-CHARGE OF AM BATTERY BANK 1, AM BATTERY BANK 2, AND THE ATM BATTERIES FOR VAM1 = VAM2 = 29.2 VOLTS AND VATM = 30.4 VOLTS

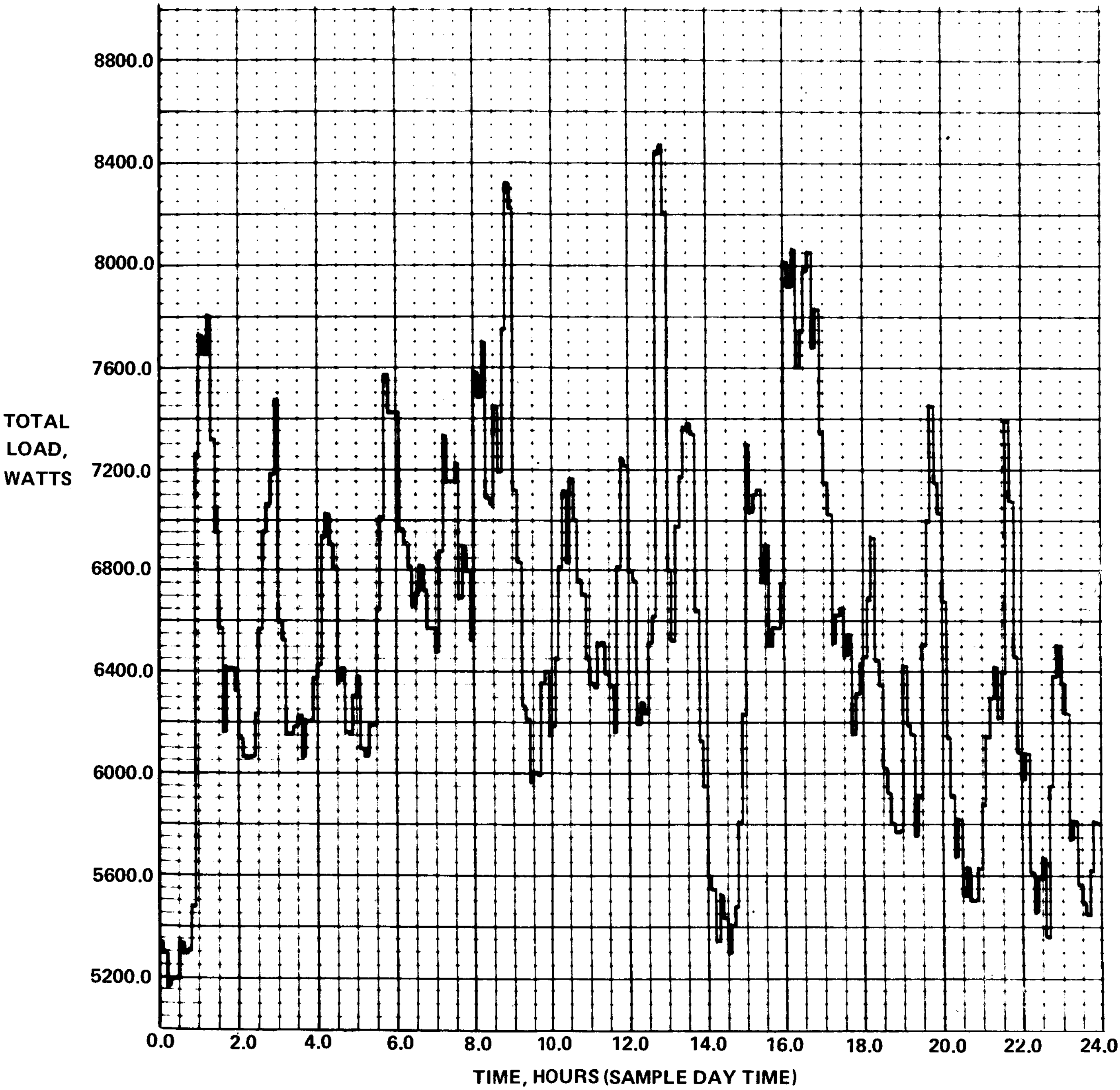


FIGURE 13 - TOTAL SKYLAB LOAD (INCLUDING DISTRIBUTION LOSSES) ON AM/OWS AND ATM ELECTRICAL POWER SYSTEMS FOR VAM1 = VAM2 = 28.8 VOLTS AND VATM = 30.4 VOLTS

APPENDIX A

BUS AND INTERFACE VOLTAGES, CURRENTS, AND LOADS
COMPUTED BY NETWORK ANALYSIS PROGRAM

The voltage profile on each AM regulated bus is shown in Figure A1 for open circuit voltage settings of VAM1 = VAM2 = 28.8 volts and VATM = 30.4 volts. The loaded bus voltage varies between 27.6 volts and 28.3 volts. Current flowing through the bus tie from regulated bus 1 to regulated bus 2 is shown in Figure A2. Figure A3 shows the voltage and current at vehicle power transfer bus 1. Negative current indicates that power is being transferred from the ATM EPS to the AM EPS. The voltages at the MDA/CSM interface and the MDA/ATM interface are shown in Figure A4. Only one profile for each interface is shown. At each interface the voltage drops below the minimum allowable voltage (28.3* volts at the MDA/ATM interface and 27.5** volts at the MDA/CSM interface). Increasing the AM regulated bus open circuit voltage settings to 29.2 volts raises the voltages just above the minimums as shown in Figure A5.

Figures A6 through A10 show the actual load, the voltage, and the current on the AM EPS control bus, the AM load bus, the OWS load bus, the CM load bus, and the ATM load bus. Only one bus, the one showing the greatest variation, is shown for each module. When voltage and current constraints are identified for each bus, future work should include examination of the appropriate included profiles to determine if any constraints are violated.

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*Skylab Program Operational Data Book, Volume IV, MSC-01549, December 1970.

**Minutes of the 15th Skylab Electrical Panel Meeting, Agenda item 15.11, March 1971.

APPENDIX B

TEMPERATURE PROFILE EQUATIONS FOR SOLAR INERTIAL ATTITUDE

The following curve-fit equations apply to the sunlit portion of the orbit and are derived from the temperature profiles of Reference 5. The equations are general in that they apply for any value of β and η within the limits as shown. Both angles are in degrees and the absolute value of β must be used.

$\eta \leq -30°$: $T = 126 - (DX+EX^2+FX^3)$

$$X = \eta - 30$$

$$D = 1.11555556 - (.0145013837\beta)^{2.08575442}$$

$$E = [24 - (.253042077\beta+.01429962\beta^2-.000210086195\beta^3)]/1000$$

$$F = (-39.50627+.219985842\beta^2-.00304979937\beta^3)/10^6$$

$-30° \leq \eta < 20°$ $T = 126 + (2C-4)[\sin(\pi(\eta+30)/100)]^{.8}$

$$C = (39-A)/2$$

$$A = (\beta/5.434)^{1.3566}$$

$\eta > 20°$: $T = Y - Z$

$$Y = 122 + C + C\cos[\pi(\eta-20)/115]$$

$$Z = [(60-\beta)/20]\sin[\pi(\eta-20)/115]$$

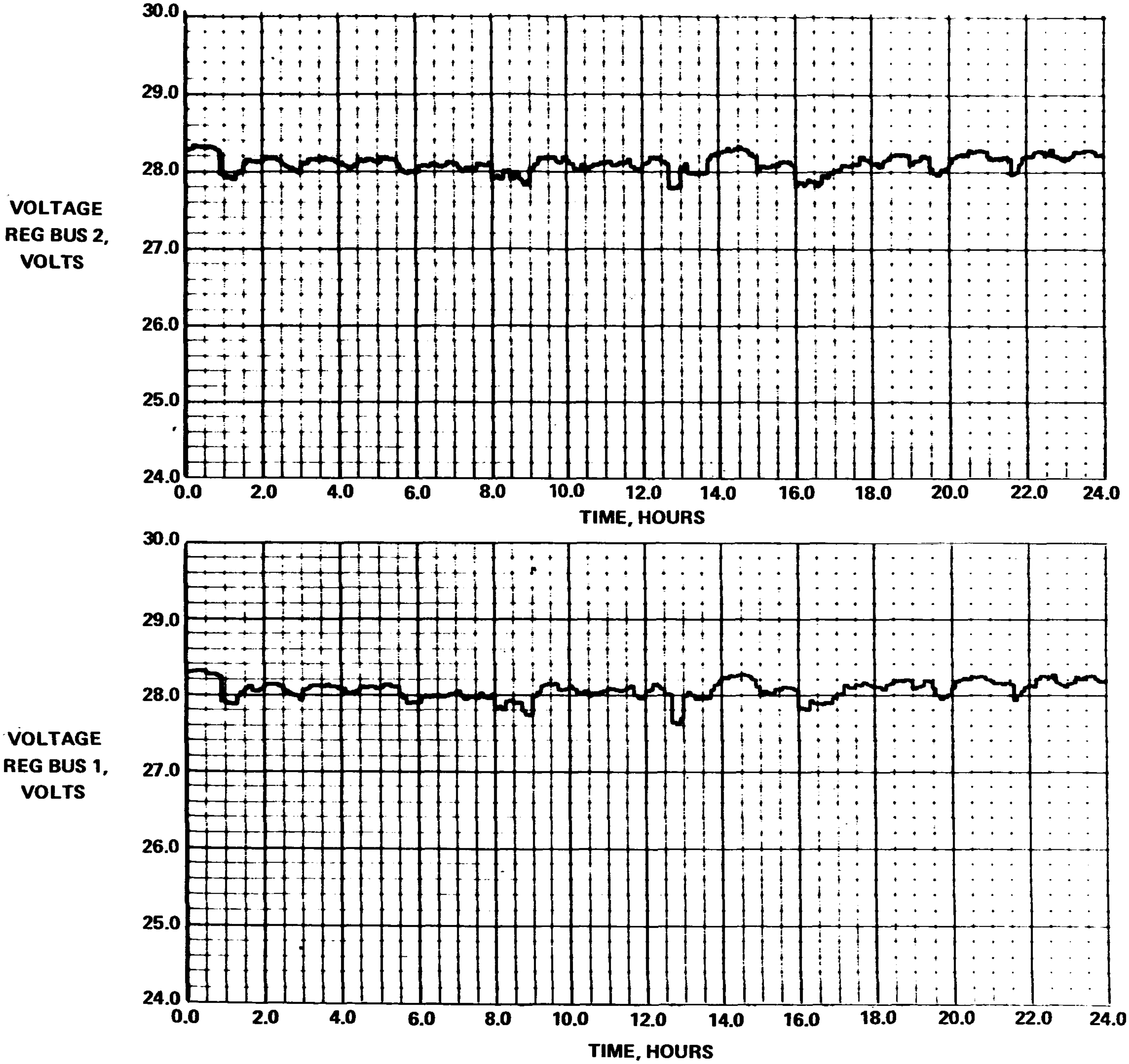


FIGURE A1 - VOLTAGE PROFILES FOR AM REGULATED BUS 1 AND BUS 2
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

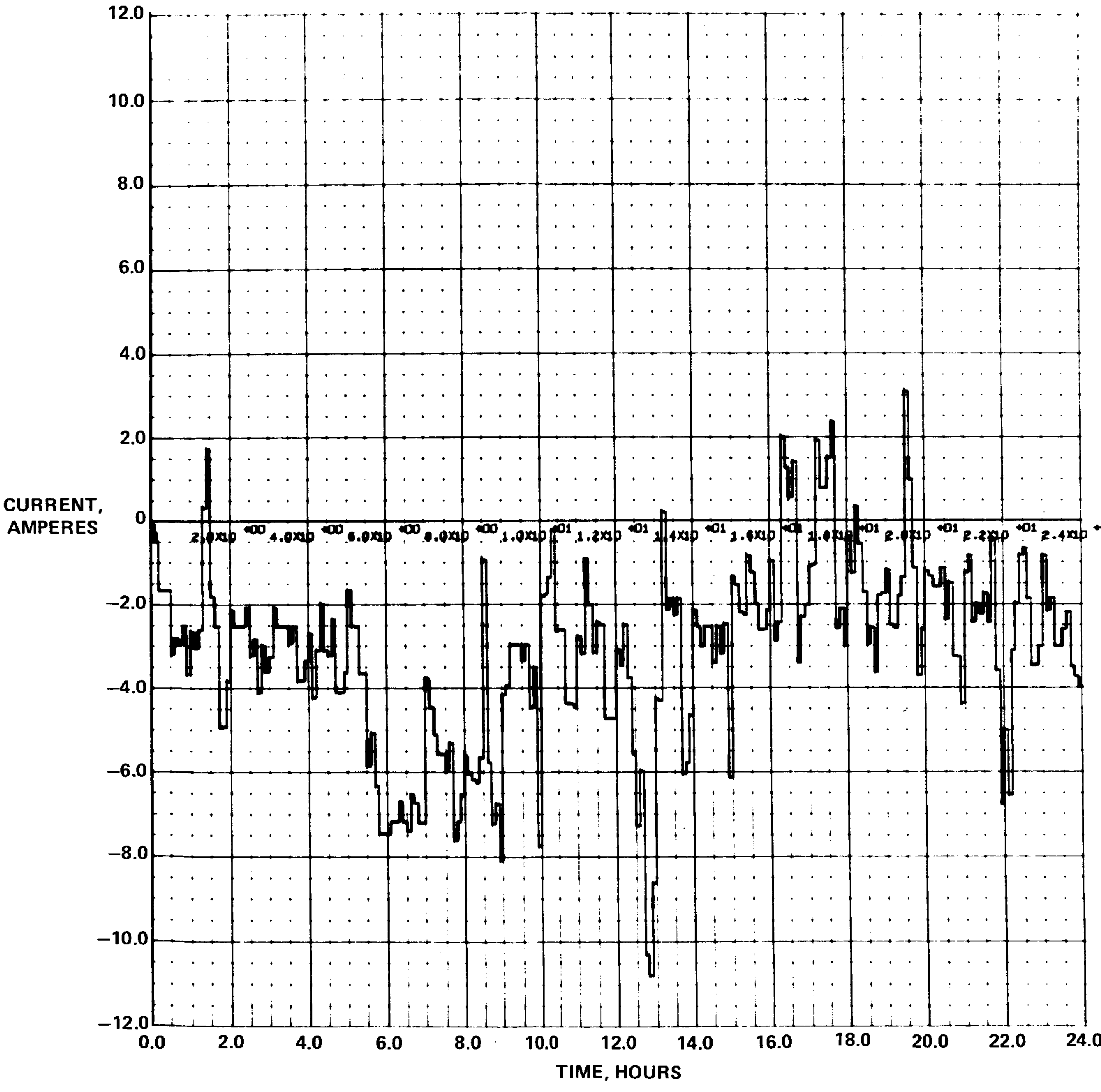
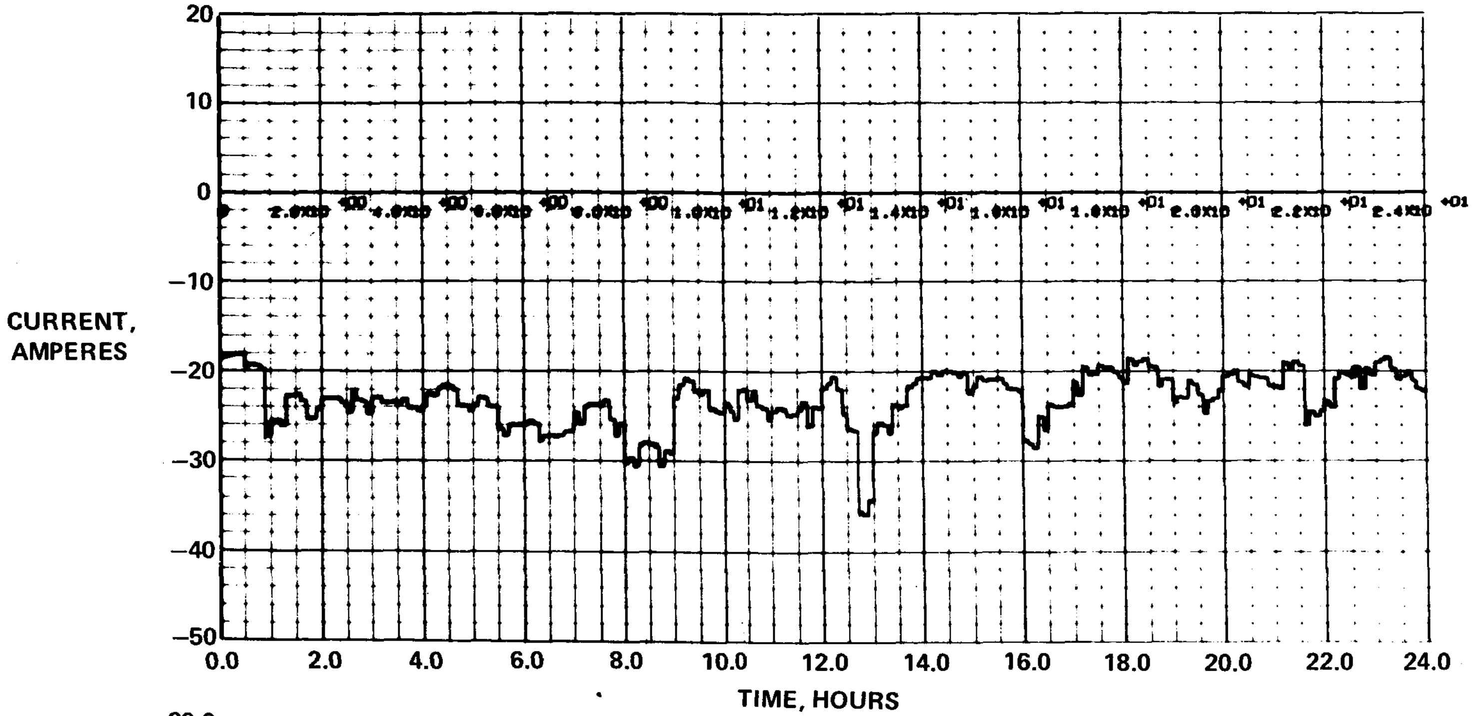


FIGURE A2 - CURRENT FLOWING THROUGH THE BUS TIE FROM AM REG BUS 1 TO AM REG BUS 2 (VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)



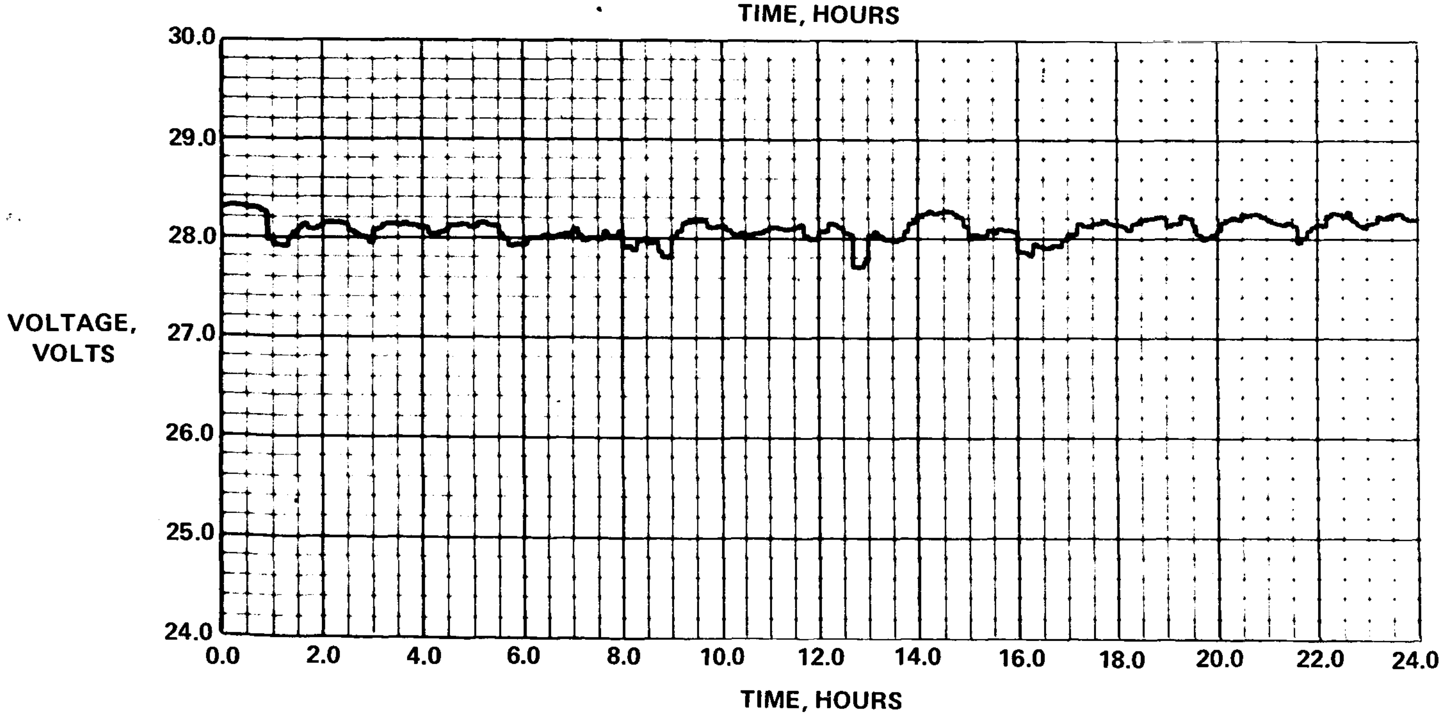


FIGURE A3 - VOLTAGE AT TRANSFER BUS 1 AND CURRENT TRANSFERRED FROM AM TO ATM EPS. (VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

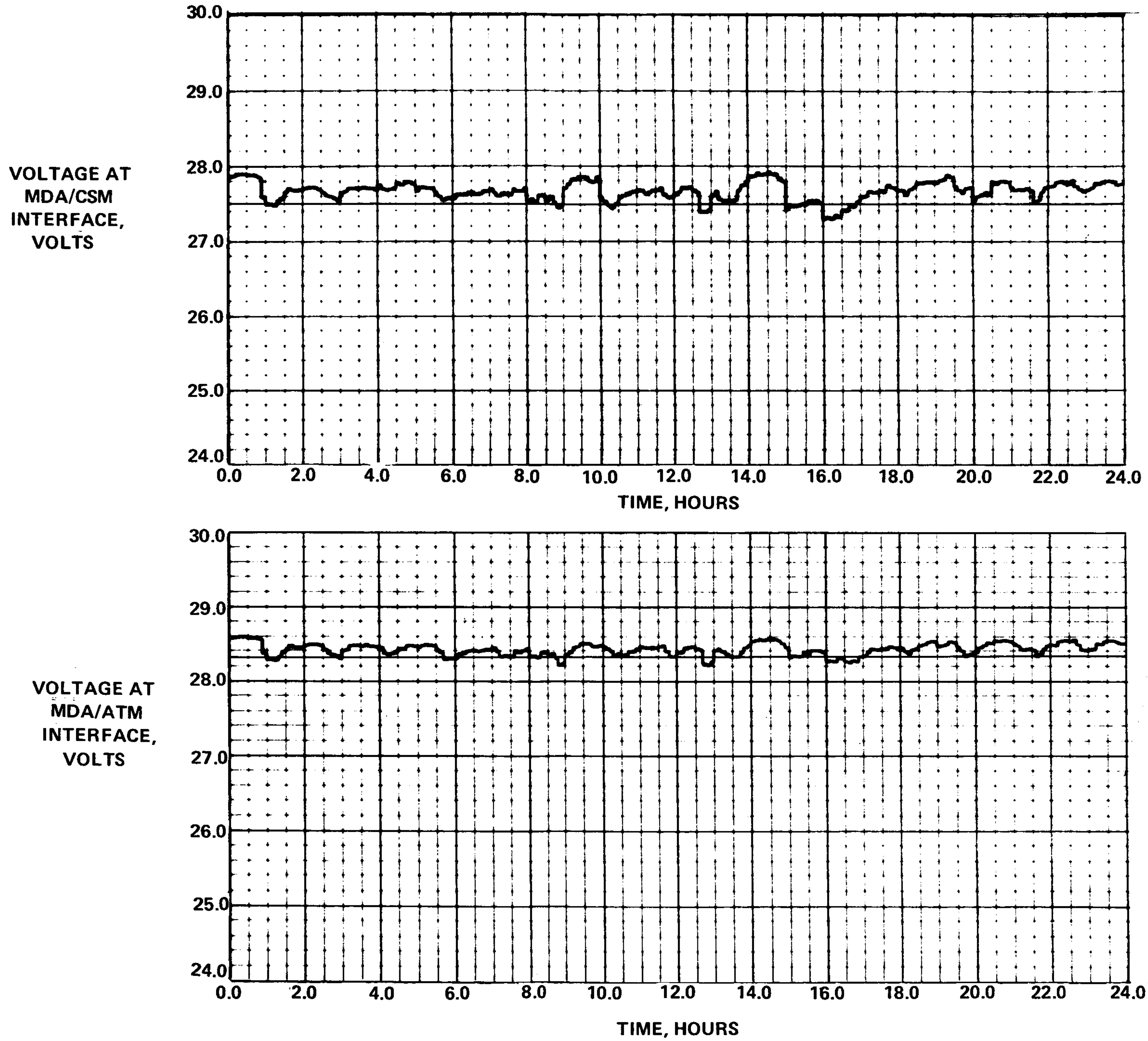
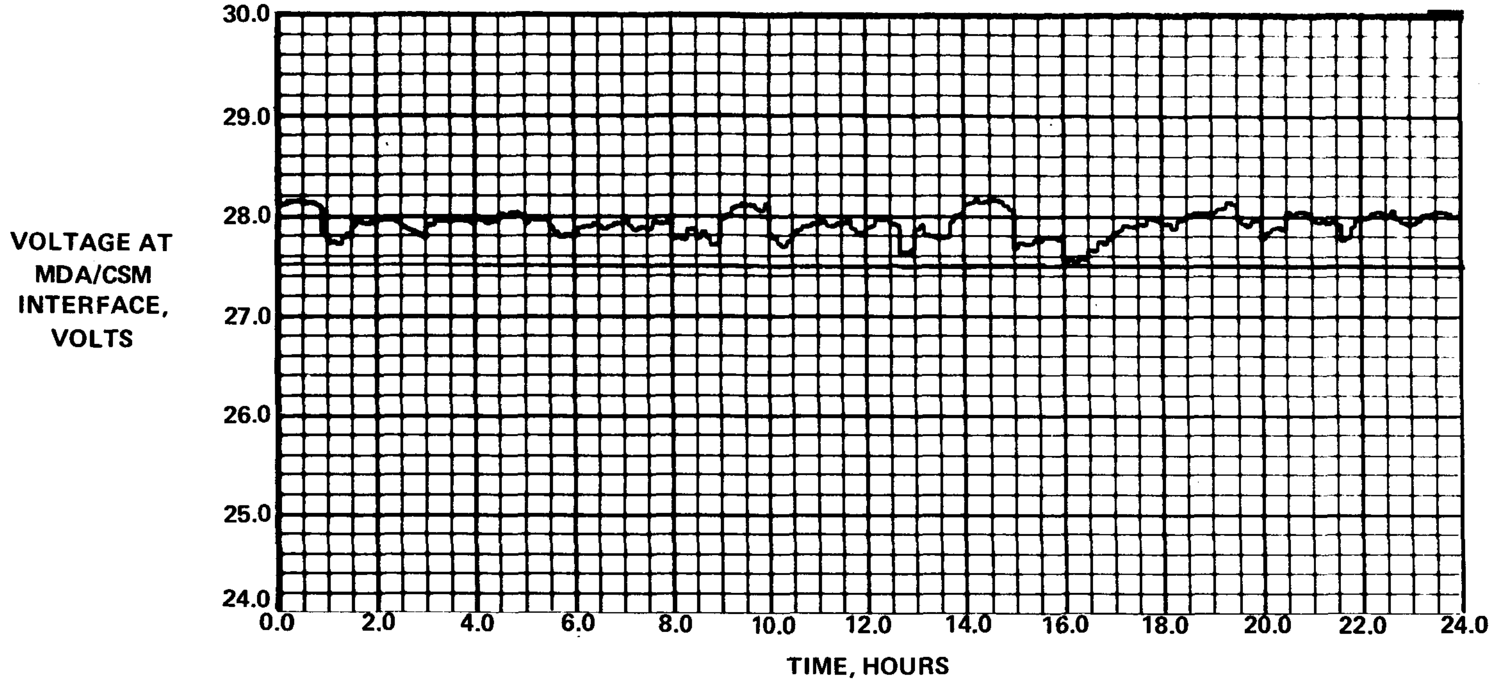


FIGURE A4 - VOLTAGE PROFILES AT MDA/CSM AND MDA/ATM INTERFACES
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)



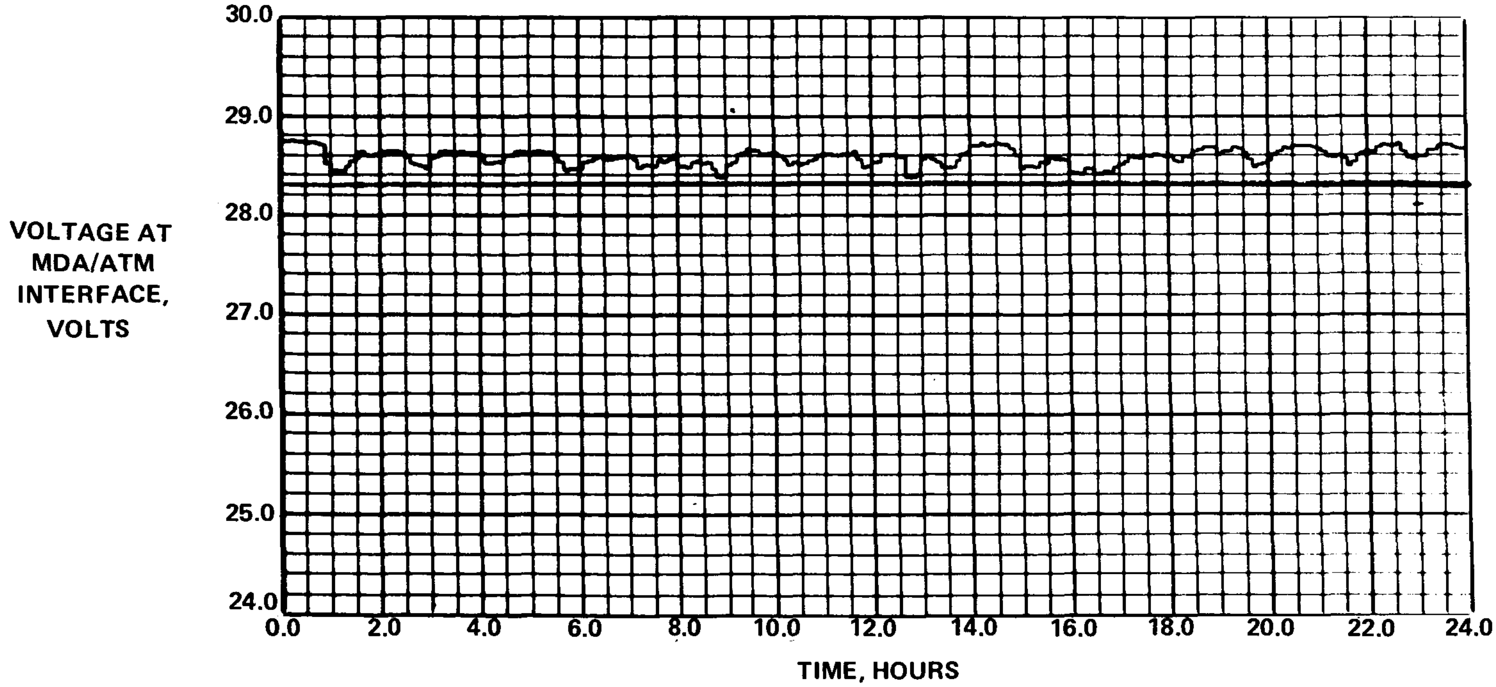


FIGURE A5 - VOLTAGE PROFILES AT MDA/CSM AND MDA/ATM INTERFACES
(VAM1 = VAM2 = 29.2 VOLTS; VATM = 30.4 VOLTS)

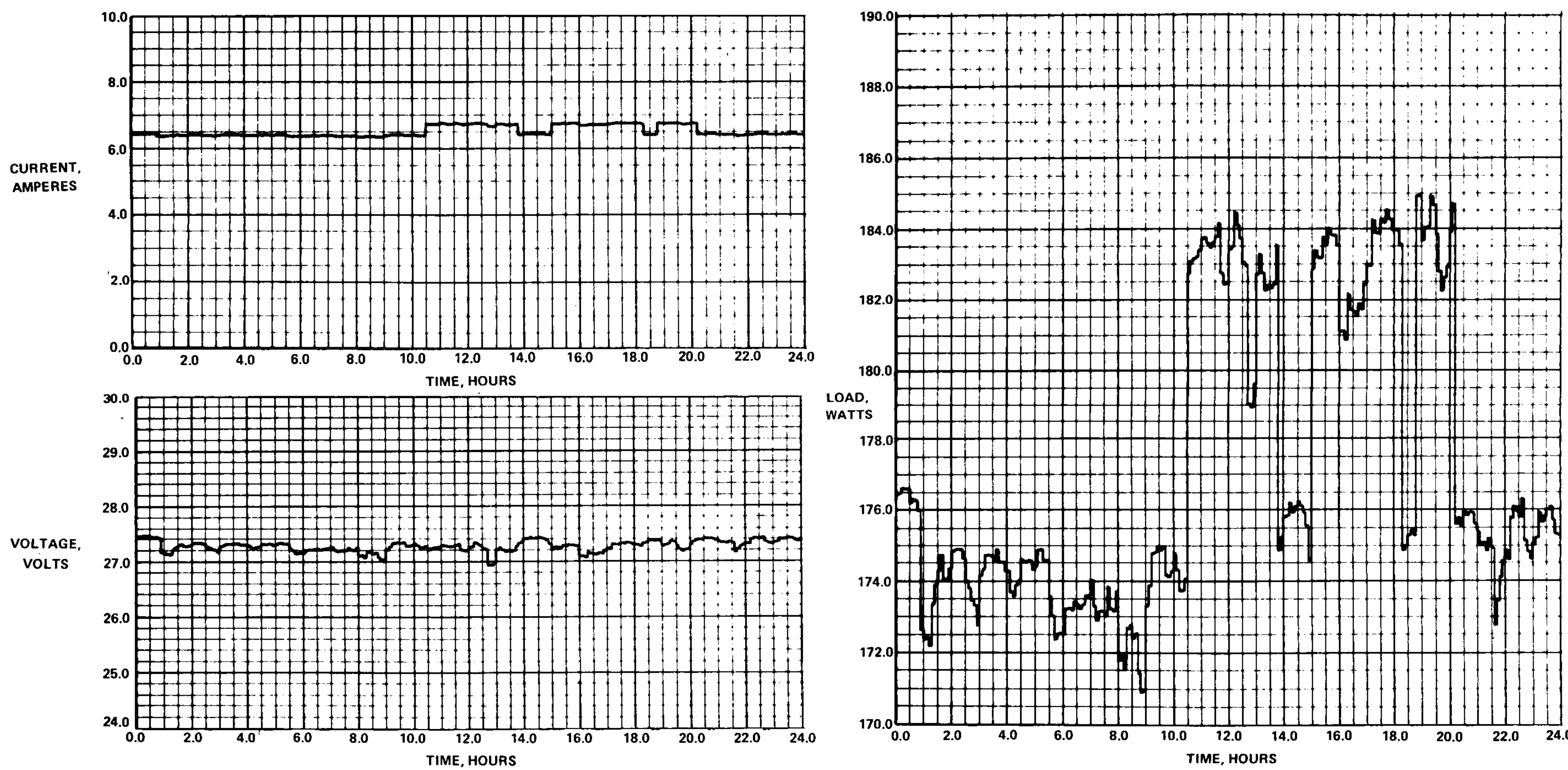


FIGURE A6 - VOLTAGE, CURRENT, AND LOAD PROFILES ON AM EPS CONTROL BUS 1
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

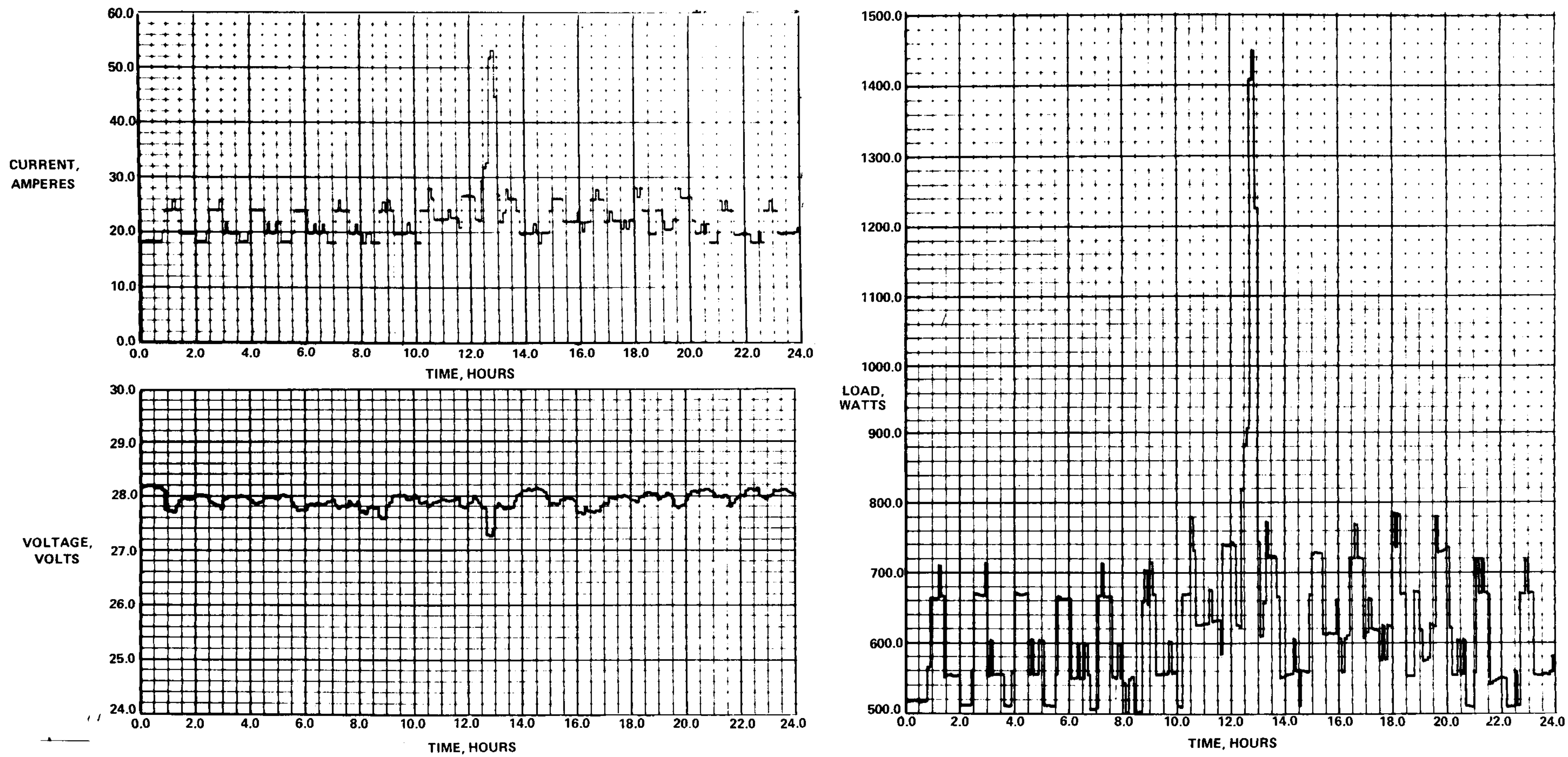


FIGURE A7 - VOLTAGE, CURRENT, AND LOAD PROFILES ON AM LOAD BUS 1
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

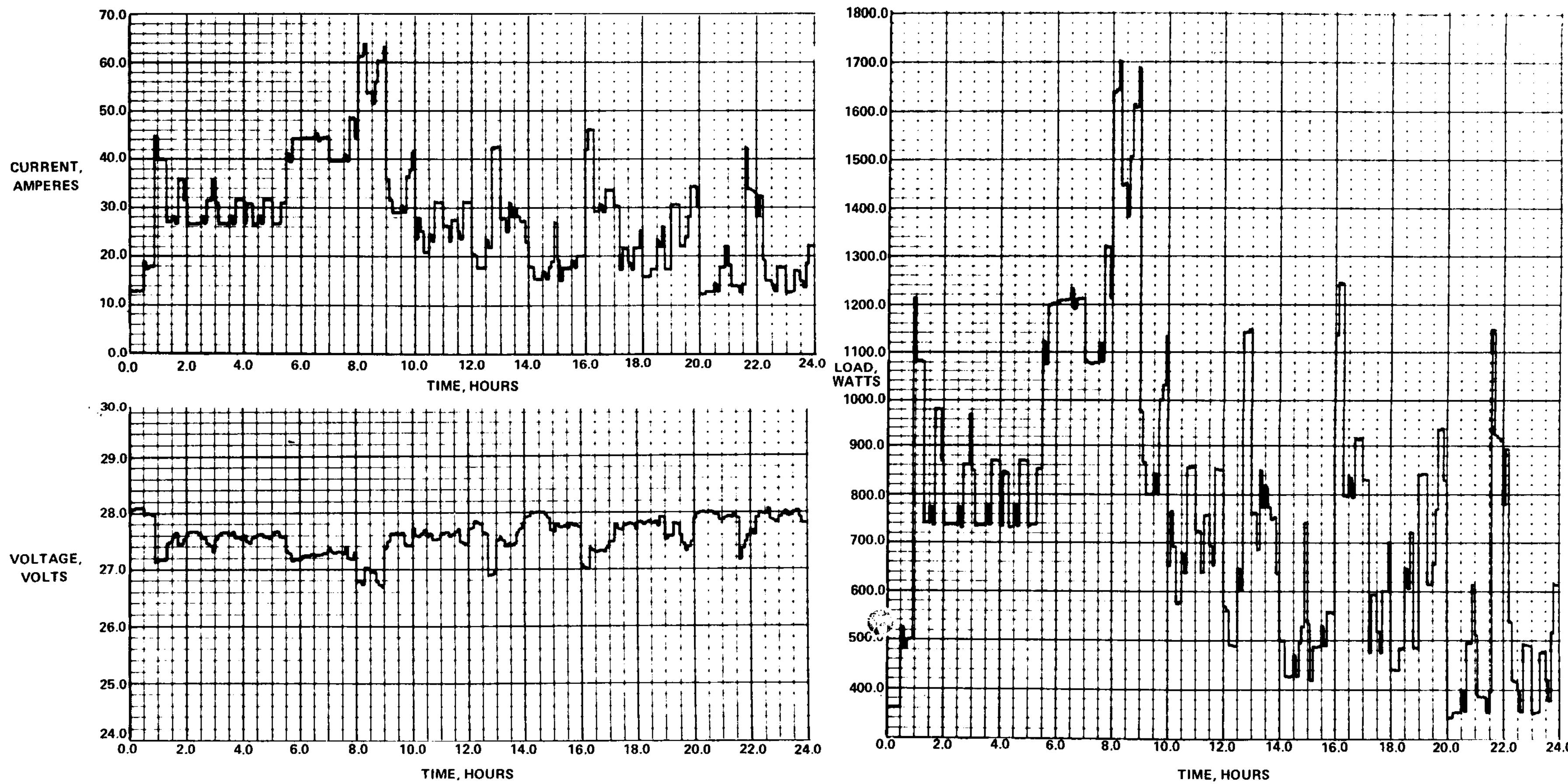


FIGURE A8 - VOLTAGE, CURRENT, AND LOAD PROFILES ON OWS LOAD BUS 1
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

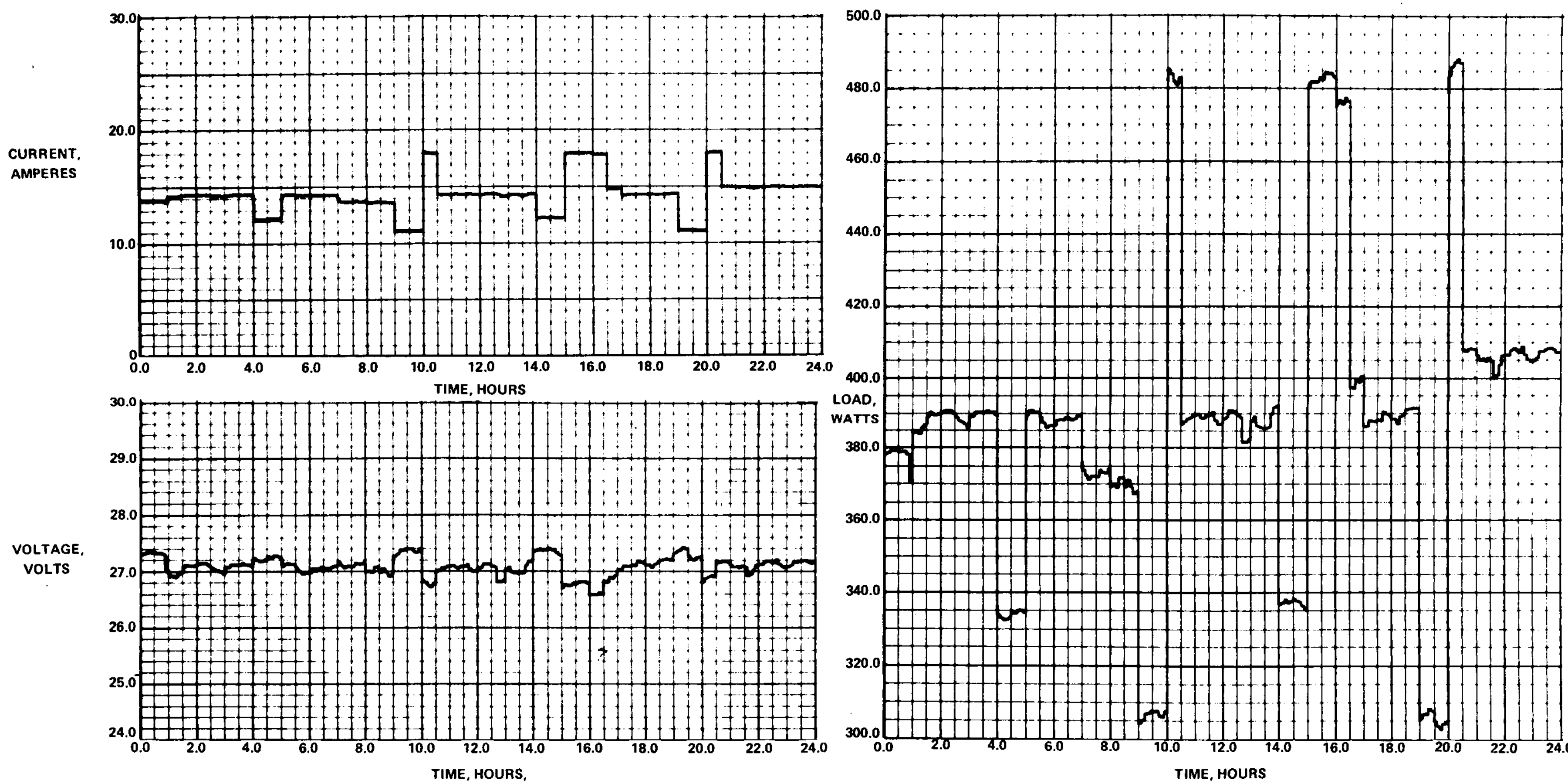


FIGURE A9 - VOLTAGE, CURRENT, AND LOAD PROFILES ON CM BUS B
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

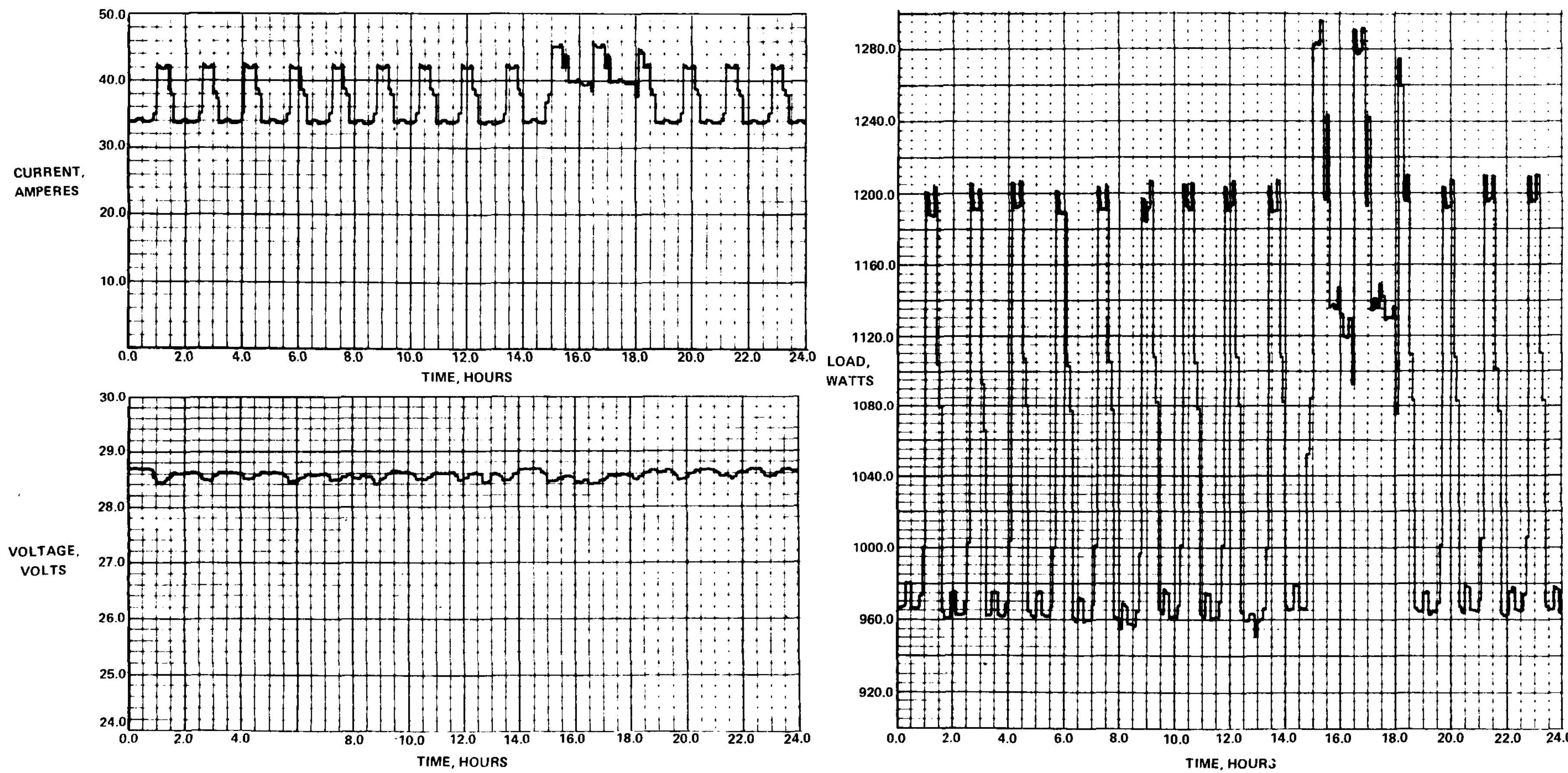


FIGURE A10 - VOLTAGE, CURRENT, AND LOAD PROFILES ON ATM LOAD BUS 1
(VAM1 = VAM2 = 28.8 VOLTS; VATM = 30.4 VOLTS)

Subject: Evaluation of the Skylab Electrical Power System for a Particular Mission Day - Case 620

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